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ABSTRACT

Designed to serve as a complement to the Unesco Technical Papers in Marine Science, this report concentrates on theoretical and practical problems of geological mapping of the sea floor. An introduction is given to geological mapping procedures at continental margins as well as some practical recommendations taking as an example the African region which is among the least studied regions of the world. Chapter contents include: (1) "Sedimentation Conditions near the Shores of Africa"; (2) "Nomenclature and Classification of Sediments"; (3) "Mapping Bottom Sediments"; (4) "Distribution and Composition of Bottom Sediments near the Shore of West and Central Africa"; and (5) "Modern and Ancient Interplay between the Environment and Sediments." It is suggested that the principles identified in this report for studying and mapping sediments in the eastern part of the Atlantic Ocean can be applied to other regions such as the Mediterranean and the western part of the Indian Oceans. Bibliographic notes are provided, and the abstract is presented in five languages in addition to English. (ML)

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37

Principles of geological mapping of marine sediments

(with special reference to the African continental margin)

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Principles of geological mapping of marine sediments

(with special reference to the African continental margin)

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PREFACE

Unesco Reports in Marine Science are designed to serve specific programme needs and to report on developments in projects conducted by the Unesco Division of Marine Sciences, including those involving collaboration between the Division and the Intergovernmental Oceanographic Commission.

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ABSTRACT

The present study is devoted to theoretical and practical problems of geological mapping of the sea floor. The objective of the work is to give, in a relatively small volume, an introduction to geological mapping procedures at continental margins, as well as some practical recommendations taking as an example the African region which is among the least studied regions of the world.

Geological mapping, including mapping of the ocean floor, is the first necessary step to a prognosies of the existance of different mineral deposits; it serves also as a basis to their prospecting. In the first place it is applied to so called sedimentary mineral deposits such as construction materials, heavy minerals, phosphates, etc.

Marine geological mapping requires knowledge of the main environmental processes which form bottom sediments and determine their composition. Hence the initial section of this work on the basic mechanisms of sedimentary processes provides the basis for the following chapters which are devoted to mapping techniques and sediment nomenclature. The reader will find here the principles for analytical mapping using quantitative methods for the measuring of those parameters which determine the concerned types of sediment. The paper also gives rules for sediment classification and nomenclature.

The closing chapters are devoted to the distribution and composition of bottom sediments near the shores of Africa, the modern and ancient relationships between sediments and the environment, as well as other topics.

RESUME

La présente étude porte sur les problèmes théoriques et pratiques que pose la cartographie géologique des fonds marins. L'objectif de cet ouvrage est de présenter, sous une forme assez ramassée, un aperçu des méthodes de cartographie géologique appliquées pour les marges continentales et de formuler certaines recommandations concrètes fondées sur l'exemple de l'Afrique, qui est l'une des régions les moins étudiées du monde.

La cartographie géologique, y compris celle du fond des océans est un préalable de tout pronostic concernant la présence de différents gisements minéraux et fournit également une base pour les activités de prospection. Son champ d'application privilégié est l'étude des dépôts dits sédimentaires : matériaux construits, minéraux lourds, phosphates, etc.

La cartographie géologique marine passe par la connaissance des principaux processus qui conditionnent le dépôt de sédiments au fond des océans et déterminent leur composition. La première section de cet ouvrage, où sont décrits les mécanismes fondamentaux de la sédimentation, fournit donc une base pour les chapitres suivants, qui ont trait aux techniques de cartographie et à la nomenclature des sédiments. Le lecteur y trouvera les principes de la cartographie analytique comportant l'utilisation de méthodes quantitatives de mesure des paramètres qui déterminent les types de sédiments en question. Des règles sont également énoncées pour la classification et la nomenclature des sédiments.

Les derniers chapitres traitent de la distribution et de la composition des sédiments des fonds marins à proximité des côtes de l'Afrique, des relations actuelles et anciennes entre les sédiments et l'environnement et de diverses autres questions.

RESUMEN

El presente estudio versa sobre los problemas teóricos y prácticos de la cartografía geológica del suelo del océano. Su objetivo es presentar en un volumen relativamente pequeño una introducción a los procedimientos de cartografía geológica en las márgenes continentales, así como algunas recomendaciones prácticas, tomando como ejemplo la región de Africa que es una de las menos estudiadas.

La cartografía geológica, incluida la del suelo del océano, constituye uno de los primeros pasos para pronosticar la existencia de yacimientos de diferentes minerales y sirve además de base para su prospección. En primer lugar, se aplica a los denominados yacimientos sedimentarios de minerales como materiales de construcción, minerales pesados, fosfatos, etc.

La cartografía geológica marina supone que se conozcan los principales procesos ambientales que forman los sedimentos del suelo y determinan su composición. En consecuencia, la sección inicial en la que se estudian los mecanismos básicos de los procesos de sedimentación sirve de base para los siguientes capítulos que están dedicados a las técnicas de cartografía y a la nomenclatura de los sedimentos. El lector encontrará los principios de la cartografía analítica, que utiliza métodos cuantitativos para medir los parámetros que determinan los correspondientes tipos de sedimentos. Figuran además las normas de la clasificación y nomenclatura de los sedimentos.

Los últimos capítulos versan sobre la distribución y composición de los sedimentos del suelo cerca de las costas de Africa, las relaciones modernas y antiguas entre sedimentos y medio ambiente y algunos otros temas.

АННОТАЦИЯ

Настоящий доклад посвящен вопросам теории и практики геологического картирования дна Мирового океана. Цель работы - в небольшом объеме дать представление и практические рекомендации по геологическому картированию осадков на примере менее чем другие исследованного района Мирового океана, омывающего Африканский материк.

Геологическое картирование, в том числе картирование морского дна, является первым необходимым шагом, на основе которого делается прогноз в отношении различных полезных ископаемых, ставится их поиск и ведется разведка, а затем и добыча. Прежде всего это относится к твердым полезным ископаемым, таким как строительные материалы, россыпи, фосфориты и т.д.

Работа по геологическому картированию требует знаний основных закономерностей, формирующих осадки дна и определяющие их состав. Поэтому вопросам техники картирования гранулометрического и вещественного состава осадков, а также составления сводных карт донных осадков в разных масштабах предпослан раздел, посвященный основным закономерностям осадкообразования. Даются представления о принципе аналитического картирования, основанном на количественных методах определений осадкообразующих параметров, классификации и номенклатуре осадков.

Заключительные главы посвящены вопросам распределения и состава донных осадков у берегов Африки, а также современным и древним связям между осадком и средой.

خلاصة

هذه الدراسة مخصصة للمشاكل النظرية والعملية المتعلقة برسم الخرائط الجيولوجية لقاع البحار . والهدف من اجراء هذه الدراسة هو اعداد مجلد صغير يتضمن مقدمة تتناول طرق رسم الخرائط الجيولوجية عند حدود القارات كما يتضمن بعض توصيات عملية مطبقة على المنطقة الأفريقية على سبيل المثال وهى تعتبر من أقل المناطق حظا من الدراسة فى العالم .

ويعتبر رسم الخرائط الجيولوجية بما فى ذلك رسم خرائط قاع المحيطات الخطوة الأولى الضرورية للتكهن بوجود ترسبات معدنية مختلفة ، وهو يستخدم كذلك كأساس للتنقيب عنها . ويطبق رسم الخرائط الجيولوجية فى المقام الأول على ما يسمى بالترسبات المعدنية المتراكمة كمواد البناء والمعادن الثقيلة والفوسفات وغيرها .

ويتطلب رسم الخرائط الجيولوجية البحرية معرفة بالعمليات البيئية الرئيسية التى تؤدى الى تكوين الترسبات فى قاع البحار والتى تحدد المواد التى تتركب منها . ومن ثم يقدم القسم الأول من هذه الدراسة والذى يتعلق بالاليات الأساسية لعمليات الترسيب ، الأساس الذى ترتكز عليه الأبواب التالية المخصصة لتقنيات رسم الخرائط وتسمية الترسبات . وسيجد القارىء هنا مبادىء رسم الخرائط التحليلية بواسطة الطرق الكمية لقياس تلك البارامترات التى تحدد أنماط الترسبات المعنية . ويقدم البحث أيضا قواعد لتصنيف الترسبات وتسميتها .

أما الأبواب الختامية فهى مخصصة لدراسة توزيع وتركيب الترسبات فى قاع البحار بالقرب من شواطىء أفريقيا والعلاقات الحديثة والقديمة بين الترسبات والبيئة بالاضافة الى موضوعات أخرى .

摘　　要

本研究报告主要涉及海底地质图绘制方面的理论问题和实际问题。本研究报告的目的是用较少的篇幅介绍大陆边缘地质图绘制的步骤，并以世界上极少有人研究过的非洲地区为例提出一些切实可行的建议。

地质图绘制，包括洋底地质图绘制，是预测各种海洋矿藏分布的第一个必要步骤，同时也为勘探提供依据。地质图绘制首先应用于建筑材料、重矿物、磷酸盐等所谓的沉积矿藏方面。

海洋地质图绘制要求掌握有关主要环境过程的知识，这些过程形成了海底沉积并决定其组成。这一研究报告的开始部分论述了沉积过程的基本机制，也为后面主要论述绘图技术和沉积术语的几章提供了依据。在这一部分读者将会看到使用数量方法来测量决定有关沉积类型的参量这一分析法制图的原则。该文件还提出了沉积分类规则和术语。

最后几章主要涉及非洲海岸洋底沉积的分布和组成，沉积和环境之间的现代和古代关系以及另外几个题目。

TABLE OF CONTENTS

		Page
INTRODUCTION		1
Chapter 1	SEDIMENTATION CONDITIONS NEAR THE SHORES OF AFRICA	3
Chapter 2	NOMENCLATURE AND CLASSIFICATION OF SEDIMENTS	29
Chapter 3	MAPPING BOTTOM SEDIMENTS	52
	General Principles	52
	The Technique of Granulometric Mapping	53
	The Technique of Material Composition Mapping	61
	The Compiling of General Bottom Sediment Maps With Different Scales	67
	Lithologic-Radiometric Mapping	69
	Magnetic-Mineralogical Mapping (Survey)	74
	Investigation with Side-Scanning Sonars and Continuous Seismic Profiling	76
	Additional Investigations by Means of Underwater Photography and Television	79
	Additional Investigations with the Help of Divers and Manned Vehicles	79
Chapter 4	DISTRIBUTION AND COMPOSITION OF BOTTOM SEDIMENTS NEAR THE SHORE OF WEST AND CENTRAL AFRICA	81
	Coarse-clastic sediments (larger than 1mm)	81
	Sands (0.1-1.0 mm)	82
	Coarse aleurites and fine aleuritic muds	86
	Aleuritic-pelitic and pelitic muds	88
Chapter 5	MODERN AND ANCIENT INTERPLAY BETWEEN THE ENVIRONMENT AND SEDIMENTS	91

INTRODUCTION

There is a widely-held opinion, that the mapping of bottom sediments is very simple, consisting in plotting sample results on a map of a certain scale, and then mechanically delimiting areas of development of sediments of the same type.

The author's long experience with mapping sediments in different parts of the ocean has shown that this work is actually rather complex; it cannot be done properly without an understanding of the basic sedimentation mechanisms that determine the composition of bottom sediments and correlations among their constituent parts. These mechanisms are determined by latitudinal (climatic), cirmum-continental, vertical and tectonic considerations. Hence a section on the basic mechanisms of sedimentation processes, with examples taken from waters surrounding Africa, precedes, in the present work, chapters devoted to mapping technique and sediment nomenclature.

The second section of the present work deals with sediment nomenclature and classification, as they seem best suited to the technique of compiling maps with different scales. The author proposes a bidimensional system of nomenclature, classification and mapping, with both sediment material composition and granulometry taken into consideration. Information is provided about simpler and more precise methods for determining sample coordinates, about the use of geophysical methods, underwater photography and bottom investigation by divers or manned underwater vehicles.

Methods of sample acquisition and field study techniques as well as the apparatus used for such purposes, are discussed separately, as is laboratory analysis of samples.

The concluding section indicates how the formation mechanisms, discussed briefly in Section I, actually apply to specific types of bottom sediments. Thus the study is structured to flow from general principles to methods for investigating, classifying and mapping sediments, then to specific sediment types, as studied and mapped in the waters around Africa on the basis of the proposed classification and nomenclature system.

Such an approach is necessary to substantiate the new system of bottom sediments mapping, which yields a very objective demonstration of the sedimentation process, and provides a basis for acquiring important additional information about the physical properties of sediments.

The proposed system can be applied with qualitatively different types of equipment, from simple boats or launches to the most sophisticated research vessels.

During regional or local studies, various questions could arise, and the author would be happy to answer them at the following address: Moscow 117218, 23 Krasikov Street, Shirshov Institute of Oceanology of the USSR Academy of Sciences. These principles for studying and mapping sediments, demonstrated in the eastern part of the Atlantic Ocean, where sediments were studied most thoroughly, can be applied to other regions such as the Mediterranean and the western part of the Indian Ocean.

The author will be grateful for any remarks.

Chapter 1. SEDIMENTATION CONDITIONS NEAR THE SHORES OF AFRICA

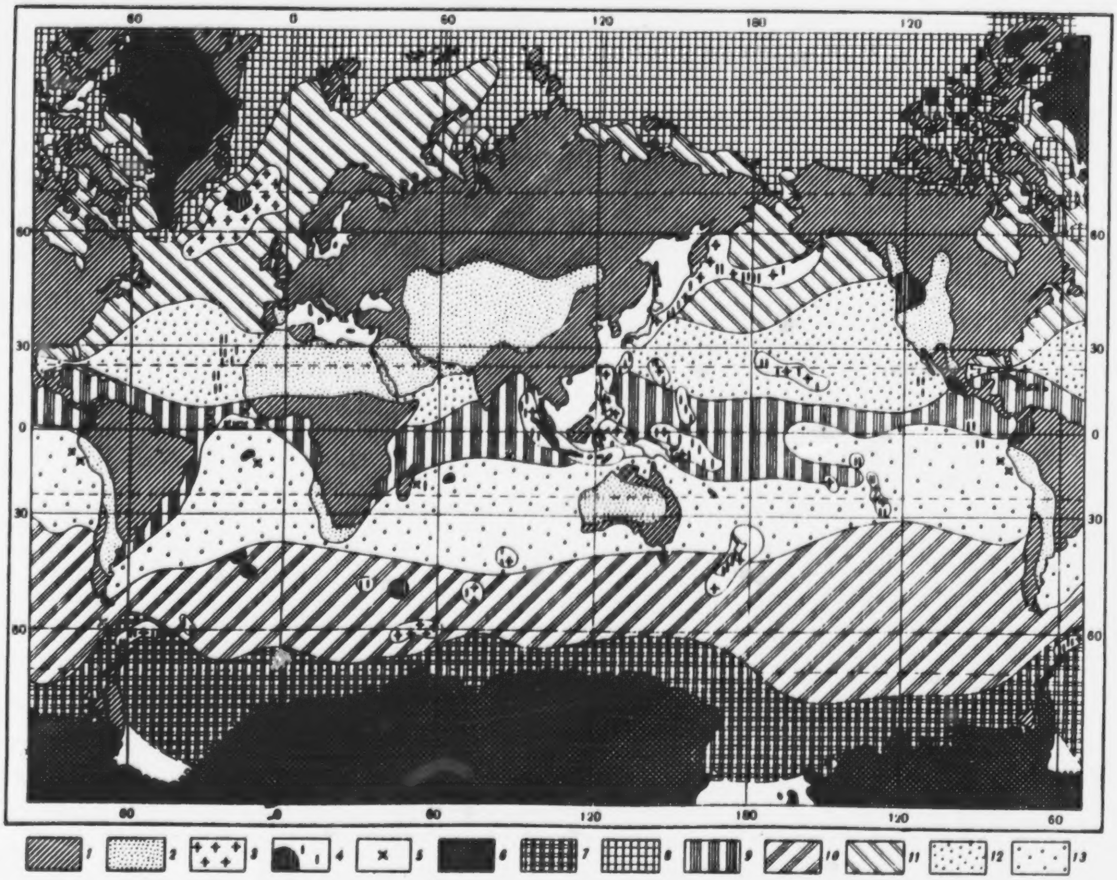
The geographical position, geology and relief of the African continent to a great extent determine the specific nature of sedimentation in adjacent regions of the Atlantic Ocean. The most northerly point of the continent, Cape Blanco, is situated at 34°51 N, and the most southerly, Cape Agulhas, at 34°51 S. Thus the greater part of the continent is within the equatorial and (north and south) tropical zones, and only a small part in subtropical zones (fig. 1). Delivery of terrigenous material to bottom sediments from land is determined by latitude as is the formation of biogenous and authigenous material in the adjoining ocean.

The amount of sedimentary material delivered from the continent of Africa to the ocean is determined by climate, and by the spillway's geology and relief. About 15% of the continent is occupied by desert, from which only eolian material is carried out; in particular from the deserts of North Africa. Observations made from ships and oceanic islands have established that fine aerosolic material from Africa can be carried above the ocean for over 6,000 km. But the greatest quantities of aerosolic material fall out over the shelf and the continental slope; this is the main type of terrigenous material in the north and south arid zones.

Indigenous land rock weathering rates in the equatorial zone are approximately 10 times higher than in moderate humid zones, and much higher than in arid zones. Therefore, the main mass of sedimentary material is deposited in the world's oceans from a fairly narrow equatorial zone (roughly ± 10°). According to the author's calculations, more than 500 tons/km^2 of sedimentary matter are washed away in the spillways of equatorial zones and this digue can climb to 2,000 tons/km^2. The equatorial zone is responsible for approximately 3/4 (76%) of all sedimentary material delivered to the ocean from land. The delivery of terrigenous material from the arid zones of Africa is approximately 15 times lower than from the equatorial humid zone.

The northern arid zone extends from Gibraltar to Cape Verde, i.e., it includes the coastal areas of Morocco, Western Sahara, Mauritania and part of Senegal (fig. 2). The northern humid zone lies to the north of it and the equatorial humid zone to the south. The southern arid zone commences to the south of the River Zaire and extends to the southernmost point of the African continent (Cape Agulhas).

A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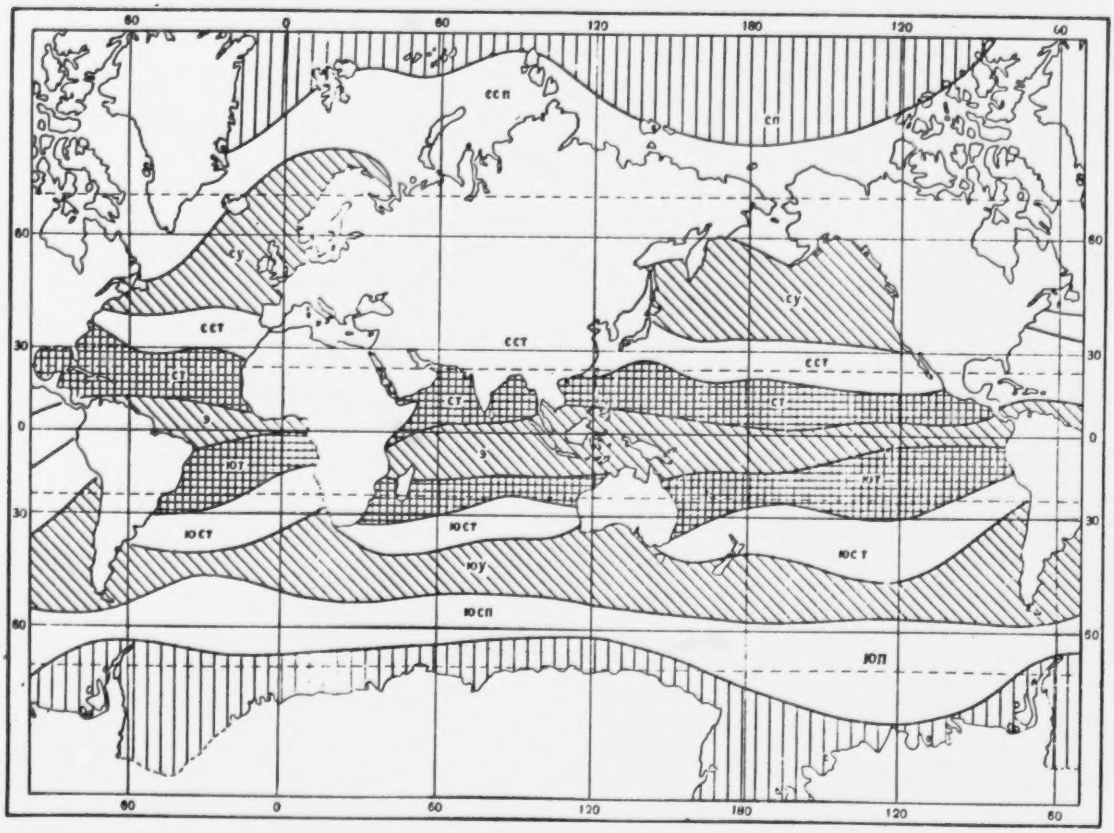
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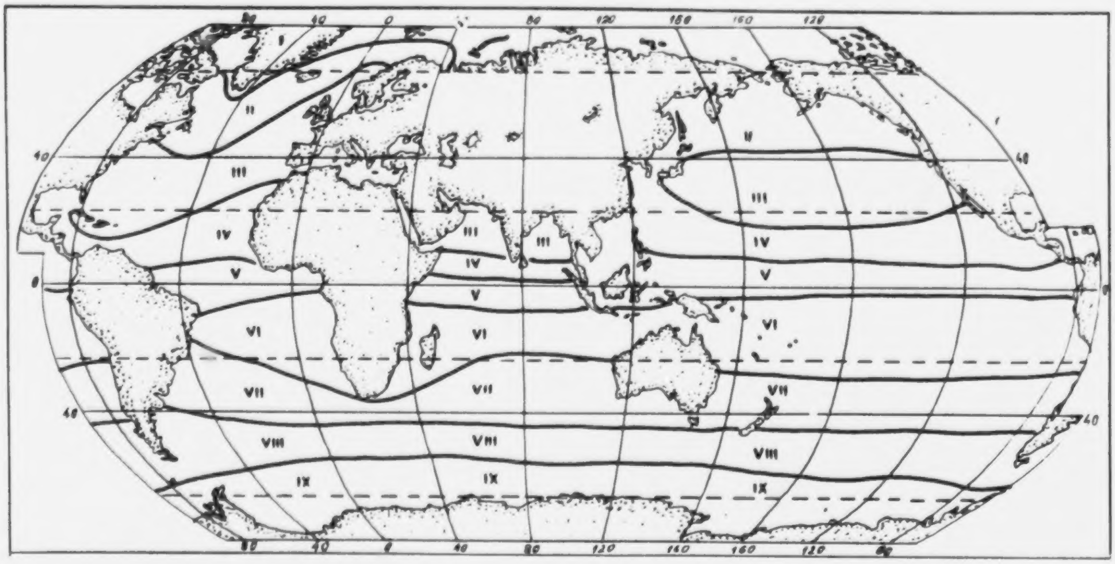


Fig. 1. Zonation of lithogenesis on continents and in oceans, and of the oceanic environment (natural zones and chemical oceanographic zones).

A - types of lithogenesis
a. On land: 1 - humid; 2 - arid; 3 - effusive-sedimentary; - 4 volcanos and volcanic regions; 5 - isolated eruptions; 6 - areas of modern glaciations (glacial type);
b. In the ocean: 7 - glacial (southern iceberg type); 8 - northern hemisphere glacial; 9 - humid equatorial; 10 - southern humid; 11 - northern humid; 12 - northern arid; 13 - southern arid.

B - natural oceanic zones
1 - northern polar; 2 - northern subarctic cold part of humid zone; 3 - northern moderate humid; 4 - northern subtropical; 5 - Northern tropical; 6 - equatorial; 7 - southern tropical; 8 - southern subtropical; 9 - southern moderate; - 10 - subantarctic; 11 - northern (southern polar).

C - chemical oceanographic zones
1 - arctic; 2 - subarctic; 3 - nothern subtropical; 4 - antarctic ical; 5 - equatorial; 6 - southern tropical; 7 - southern subtropical; 8 - subantarctic; 9 - antarctic.

In the northern arid zone there are no large rivers and dry river beds (wadis) are filled only during rare downpours. This enormous area is occupied by the drainless region of the Sahara. The southern arid zone has two large rivers, the Kunene and Orange; the main part of drainage is related to the rainless Kalahari region. Rains are infrequent in arid zones and temperatures reach +50-55°C. Extreme heating of air causes frequent sandstorms and tornados, which carry aerosolic material to the ocean, where it is transported by trade winds (fig. 2).

The drainage area of the Orange River is 1,020 km^2, with an annual run-off of 91 km^2. In terms of solid run-off it is the largest river of West Africa: its annual discharge of 153 million tons is second only to the Mississippi (500 million tons) and the Amazon (498 million tons). In fact, the solid discharge of the Orange River equals the discharges of the giant Zaire and Niger put together! The turbidity of this river is very high - about 1,700 gr/m^3, which is 5-10 times higher than that of the Zaire and Niger.

Arid zones are separated from the equatorial by rather narrow zones of semideserts - savannahs with leaf-shedding-evergreen forests. In these zones the washing away of sedimentary material is especially high, as weathering products are poorly retained by vegetation. This is also true of transitions to the moderate humid zone (semideserts - steppe-forest-steppe). The drainage area of the Orange River is situated in such conditions. Altitude is also of great importance as far as zonation is concerned in drainage areas when there is a wide gap between plateaus and mountains. In the equatorial zones of Africa, high air temperatures are combined with heavy atmospheric precipitation; in these areas there are two seasons of heavy rains (an average 11 rainy days per month) and two seasons of light rains (5-6 rainy days per month). The annual amount of precipitation reaches 1500-2000 mm, and average monthly temperatures are close to +28°C. In this area weathering crusts and soils are the thickest on our planet. Lateral weathering is accompanied by humus accumulation in upper layers. Tropical forests inhibit carrying down of the loose upper layers of weathering crust, and hence the rivers of equatorial Africa (the Zaire and the Niger) are very full-flowing (annual river run-off of 1350 and 293 km^3 respectively), but they carry relatively little sedimentary material.

According to a number of determinations (Milliman and Meade, 1982) the annual solid discharge of the Zaire amounts to 43 mln tons, and of the Niger - 40 mln tons. Together with other small rivers, the total annual solid discharge comes to about 113 mln tons in the equatorial zone.

In the coastal part of the equatorial belt we find mangrove forests with muddy sediments and characteristic biocoenosis. The main areas of sedimentary material delivery are along the periphery of the equatorial zone, where vegetation becomes more rare, i.e., at the boundary with arid zones (semideserts and savannah).

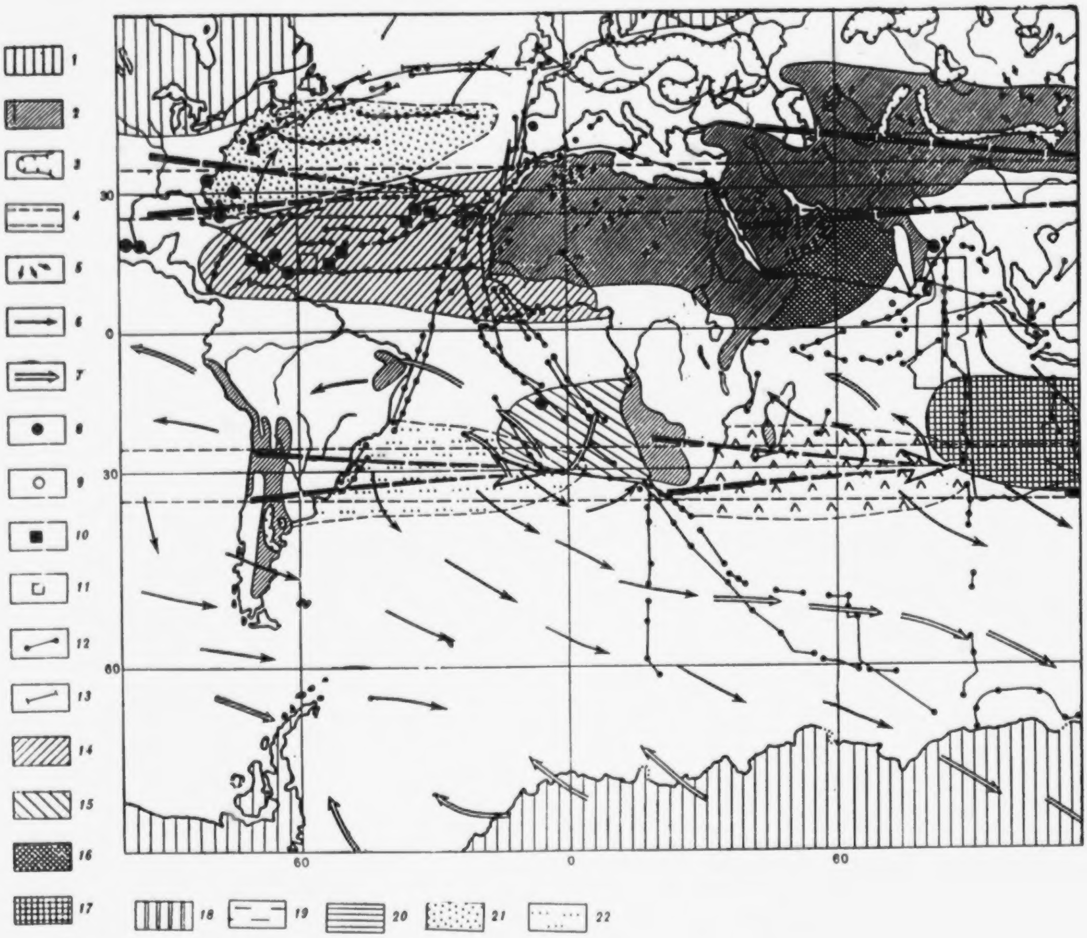


Fig. 2. Diagram of aerosol and eolian material distributing provinces over the oceans. Distributing provinces (1-3); 1 - ancient quaternary glaciations areas where sedimentaty material was scattered after glacier retreat; 2 - recent - deserts and arid continental areas; 3 - main areas of loess development. Winds and convergences (4-7); 4 - belts of filamented currents and global sinking of troposphere air masses current; 5 - wind direction in land deserts (by orientation of eolian relief forms), dominant winds (July); 6 - wind recurrence less than 50%. 7 - wind recurrence more than 50%. Studies of suspended matter above the ocean; 8 - stations of prolonged observation of aerosols (on islands, weather ships); - 9 - 11 dust fallout observations from ships at individual oceanic points; 12 - aerosol route studies in the oceans from Soviet ships (1957-1975) and according to foreign data; 13 - aerosol studies over a polygon in the western part of the Atlantic Ocean. Aerosol mineral provinces. Tropospheric (14-20); 14 - northern part of the Atlantic (quartz, feldspar, dolomite, freshwater diatomaceous, fungal spores, pollen, phytolites, palygorskite, illite, chlorite, kaolinite, montmorillonite, etc.); 15 - South Atlantic (quartz, feldspar, freshwater diatomaceous phytolites); 16 - south-western part of the Indian Ocean (carbonates, up to 80% calcite, dolomite, quartz, feldspar, palygorskite); 17 - West Australian (kaolinite, laterite material, mica, quartz-feldspar, ratio of 2-3 and more); 18 - North America (mica, quartz, feldspar, dolomite, amphiboles, soil material, anthropogenic material - talc, pesticides, etc.); 19 - East Australia (kaolinite, laterite material, mica, illite, chlorite, quartz - feldspar, ratio of 1-2, soil material); 20 - South America (mica). Filamented currents (21-22); 21 - northern part of the Atlantic (mica, soil material, fungal, spores, diatoms, anthtopogenic material, 22 - South Atlantic (uncertain).

The main effect of anthropogenic influence on oceanic sedimentation near the shores of West Africa is a constant decrease in solid run-off due to the building of ports, electric power stations and reservoirs, as well as the use of water for agricultural and industrial needs. For instance, the solid run-off of the Nile was 110 mln tones before the building of the Aswan dam, and is now zero. The building of reservoirs sharply decreases solid run-off and this tendency will evidently continue.

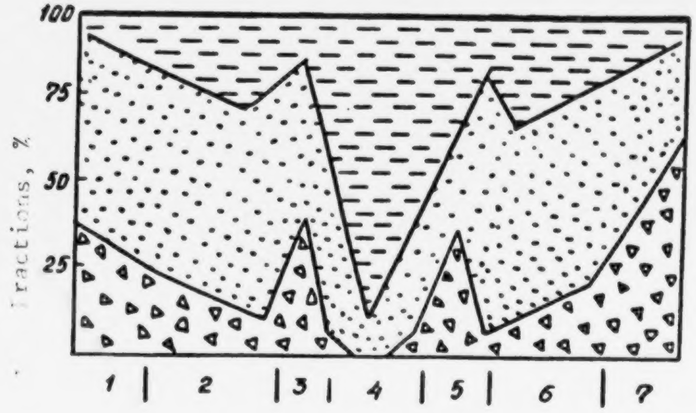
Climatic conditions also determine the granulometry and mineral content of weathering crusts and soils; these erosion products are then delivered to the ocean by rivers in the form of suspended matter (fig. 3).

In the equatorial zone chemical weathering is extreme. Thus, the clayey minerals of specific groups predominate - kaolinite, montmorillonite, gibbsite, hematite, goethite, mixed-layered minerals. Clayey minerals comprise from 80 to 99% of suspended matter in this zone's rivers, and in the remaining sandy-aleuritic fraction, weathering-resistant minerals (quartz, magnetite, zircon, staurolite) predominate.

In arid zones, due to the lack of water and sharp temperature changes, physical rather than chemical weathering predominates, leading to disintegration of primary minerals. Typical authigenous minerals of arid zones are to be found: gypsum, anhydride, halite, dolomite, palygorskite. The pelitic fraction of this zone's suspended matter is also dominated by finely dispersed minerals, as products of mechanical disintegration (in contrast to the equatorial zone, where products of chemical disintegration of minerals and rocks predominate). For pelitic fractions it is quite typical for illite, quartz and feld spar to predominate. Palygorskite, grains of dolomite, and also of many other minerals are not resistant to weathering, and hence do not occur in the equatorial zone. As has already been noted, the main part of these arid zone minerals is transferred not by rivers and streams, as in the equatorial zone, but by air in aerosol form. Peculiarities of mineral composition can be determined by studying aerosol content (Serova et al., 1979).

Weathering processes determine not only the total delivery of sedimentary material in a specific zone, and its mineral (material) composition, but also its grain size. The main type of sedimentary material delivered from land in the equatorial zone are fine pelits, and the clastic minerals content (larger than 0.01 mm) of river suspension is usually between 1 and 20%. In arid zones, the situation is different, for the content of clastic minerals in the run-off of intermittent streams reaches 30-40%. For the granulometry of these zones, it is also quite typical that almost no coarse-clastic material (larger than 1 mm) is delivered to the ocean by rivers or coming rather by coastal erosion. Hence small number of gravelly-pebbly beaches in West Africa, which distinguishes it from the moderate, and especially the glacial zones of the Earth, where beaches are composed of gravelly-pebbly material over long distances.

3 a.



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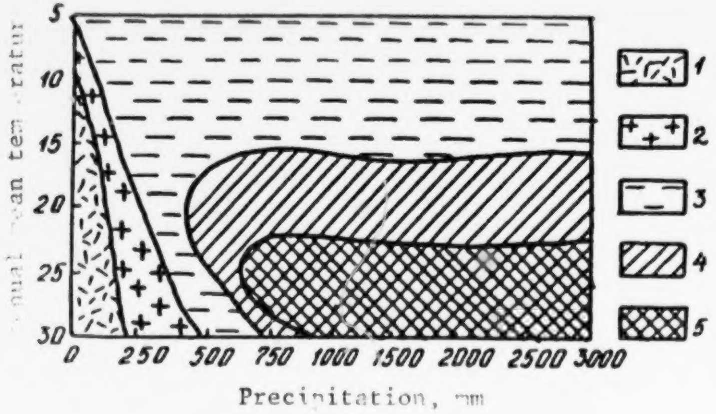

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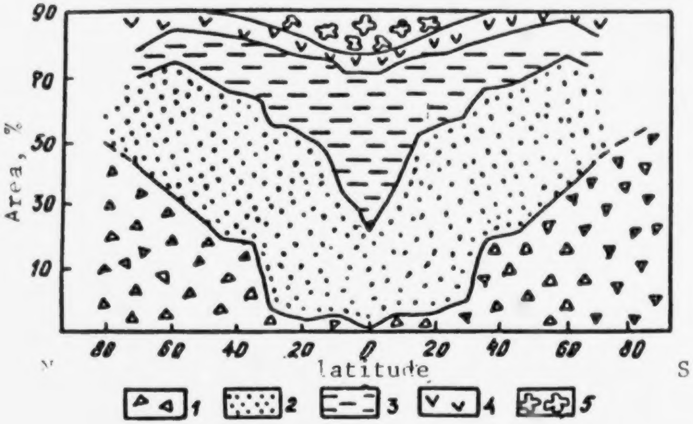


Fig. 3. Zonation of material and granulometric composition of terrigenous sediments.

A - Zonation of terrigenous material preparation in weathering crusts on the continent. Changes in granulometric composition of weathering products as a function of latitude.

B - Zonation of shelf bottom sediments. Dependence of granulometric composition of shelf sediments on latitude, according to data from 2136 shelf cross-sections.

C - Zonation of mineral composition of terrigenous material delivered to the ocean. Dependence of mineral composition of weathering crusts on average annual temperature and atmospheric sediments.

Thus, climatic zonation determines significant characteristics of the amount, granulometric composition and material content of sedimentary material, delivered from the African continent.

About 90% of suspended river material is deposited in estuaries, i.e., at the river/sea boundary. Here we find areas with extremely high sedimantation rates, where the accumulated sediments have special physical and chemical properties. The author has called them areas of avalanche sedimentation (Lisitzin, 1982; Lisitzin, 1984). Some of the material (8-10% of solid run-off) "slips" through the river/sea barrier and penetrates to the shelf, the continental slope and even into the adjoining oceanic region. Thus, the total delivery of terrigenous material to the ocean from Africa as well as its granulometric and material composition are closely related to climatic zonation. The greatest amounts are delivered from the equatorial zone (from its peripheral area at the boundary with arid zones, and the smallest from arid zones. Deposit concentrations of sedimentary material in the equatorial zone are associated with river mouths. In the arid zone, aerosolic material is scattered about arid oceanic zones more uniformly, as a function of trade-wind and stream-current directions.

Erosion of the shoreline gives rise to another source of terrigenous material. The amount of loose material - products of the shore erosion is on the whole not very large for West Africa, and is determined by the predominating development of pre-Cambrian rocks, which resist destruction. Coastal erosion is mostly active in the Niger delta coastal area.

Another type of zonation which is important for mapping of bottom sediments, is circum-continental zonation, since the contribution to sedimentation of terrigenous material decreases as one moves away from its main source - the continents.

In the distribution of terrigenous matter transported from shores, vertical zonation is usually closely connected to circum-continental zonation - the farther from the shore, the deeper the water. However, if we examine sections, situated at equal distance from the land, but at different depths, then we always observe, that more coarse terrigenous material is accumulated at the tops of underwater rises and ridges than on slopes and near the base of rises. The finer material fills the bottom depressions.

At the present stage of West Africa's development tectonic zonation is manifested in the thickness and composition of sedimentary layers. All of West Africa belongs to the passive oceanic margin, which has existed for at least 150-180 mln years. During the course of geological history, with its frequent changes in the ocean level, the shelf has been exposed many times and sedimentary material from river mouths has been transported to the bottom of the contineta1 slope, where enormously thick sedimentary layers (up to 10 km and more) have been formed. The whole area of the continental slope is predetermined by tectonic zonation as an area dominated by gravitites and associated peculiarities of sediment distribution, which must be considered while mapping.

It is characteristic of passive margins that we find listrical faults and progradation of the shelf, i.e., it rises towards the ocean. Transform margins, fined by large transform faults extending to the continent, are one type of passive margin. In West and Central Africa three such regions exist: in the Gulf of Guinea where the transform faults of the equatorial Atlantic terminate, and the East-Azores fault zone passing through Gibraltar, and near the Agulyans plateau. Tectonic zonation is seen most clearly in the middle Atlantic ridge. This is an area where the crust is erupting and hence the ocean floor age increases away from the axis of the active ridge. In the eastern part of the Atlantic Ocean the age varies from 0 to 150 mln years. The older the ocean floor, the longer the sediment has been accumulating, and consequently, the greater the thickness of the sedimentation. Therefore, moving away from the middle-ocean ridge, sediment thickness increases from 0 to hundreds of metres, and along the oceanic periphery it exceeds 1-3 km. The sediment composition also changes from sediments lying on the basalt floor, rich in Fe, Mn and other elements delivered from hydrotherms of the active ridge (basal layer of the sedimentary sequence according to Lisitzin, et al., 1973), to pelagic sediments further away from the ridge. Thus, it is possible to distinguish between lateral and vertical ranges of oceanic formations.

The second most important source of sedimentation is biogenous material - carapaces, shells and other remains of planktonic and benthic organisms. The zonation of life distribution in the ocean has been established long ago and bears the name "biological oceanic structure" (latitudinal, vertical and circum-continental zones). Land deserts usually extend into the ocean as oceanic deserts, and humid zones as biologically rich, humid oceanic zones (Lisitzin, 1974, 1977, 1978). The distribution of primary production in the Atlantic Ocean generally confirms this rule: far from the shore, arid zones are remarkably uninhabited, while primary production in the equatorial humid zone is considerably higher.

For arid zones of west continental coasts in trade-wind belts, the phenomenon of upwellings is quite characteristic - deep waters rich in biogenic elements rise towards the surface of the ocean to the zone of photosynthesis. In such places "oases in the desert" appear - areas with exceptionally high primary production values, which is reflected in the type of deposits, quite unusual for arid zones, greatly enriched by organic matter, phosphorous, amorphous silica and a number of related elements and compounds.

The distribution of primary production also determines the distribution of zooplanktonic organisms - foraminifera, pteropodes, radiolarians, etc, (figs. 4-7). This is precisely why absolute masses of carbonaceous accumulation are considerably higher in the equatorial zone of the Atlantic, than in arid zones (fig. 8). One also observes a rise in the absolute mass of silica accumulation, related to diatoms, radiolarians and to a lesser degree to silicoflagellates.

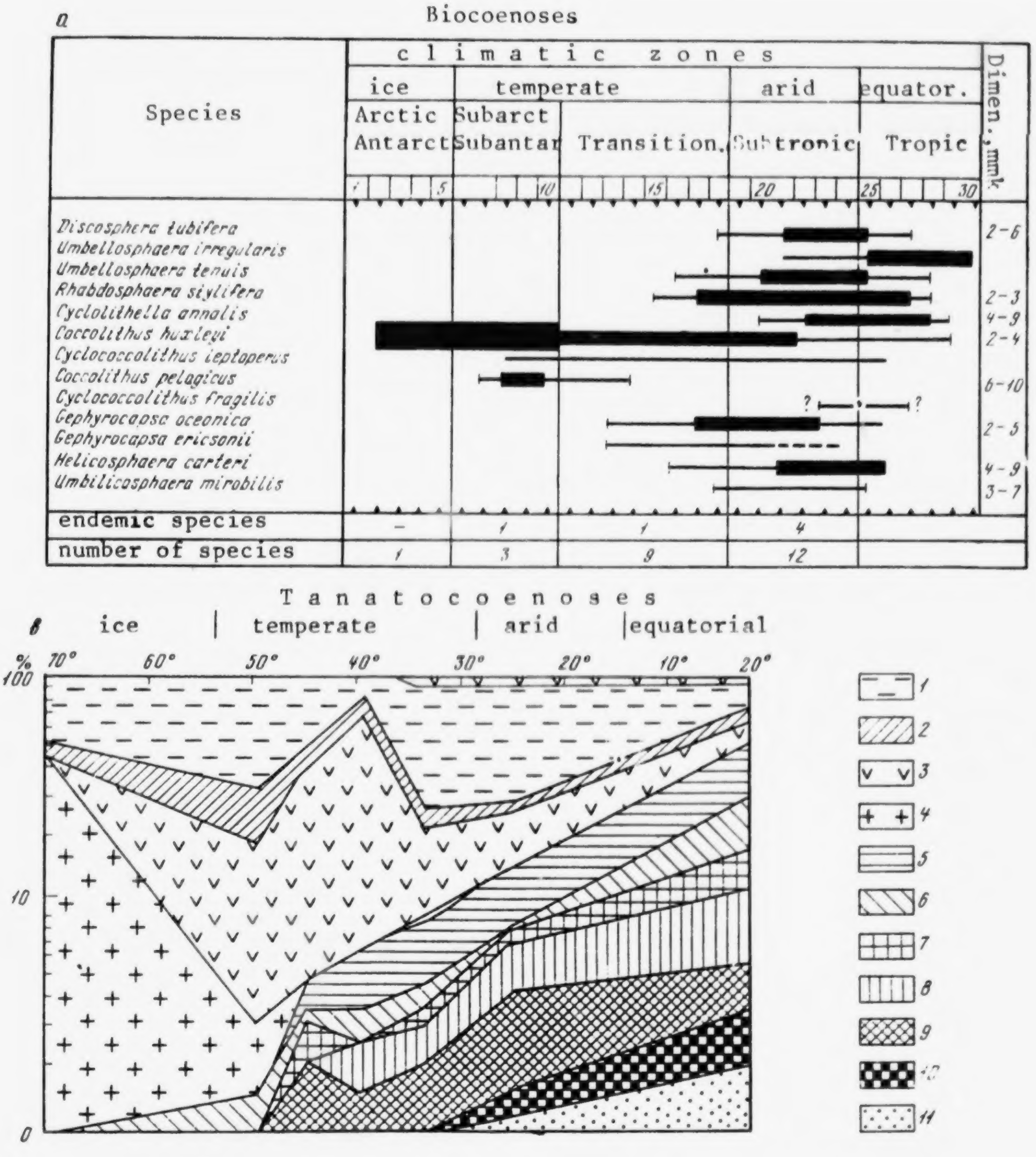


Fig. 4. Climatic (latitudinal) zonation of distribution of the most characteristic species and coenoses of coccolithophorids in plankton, in comparison with bottom sediments of the Atlantic Ocean. Zones of lithogenesis are shown at the top, and lower-down - biological zones and surface water temperatures (°c). A - individual species and biocoenoses of plankton. B - individual species and thanatocoenoses in the surface sediment layer. Species: 1 - Coccolithus huxleyi; 2 - Coccolithus leptoporus; 3 - Gephyrocapsa oceanica; 4 - Coccolithus pelagicus; 5 - Umbilicosphaera mirabilis; 6 - Helicosphaera carteri; 7 - Cyclococcolithus tragilis; 8 - Rhabdosphaera tenuis; 9 - Umbellosphaera irregularis; 10 - Cyclolithella annulus.

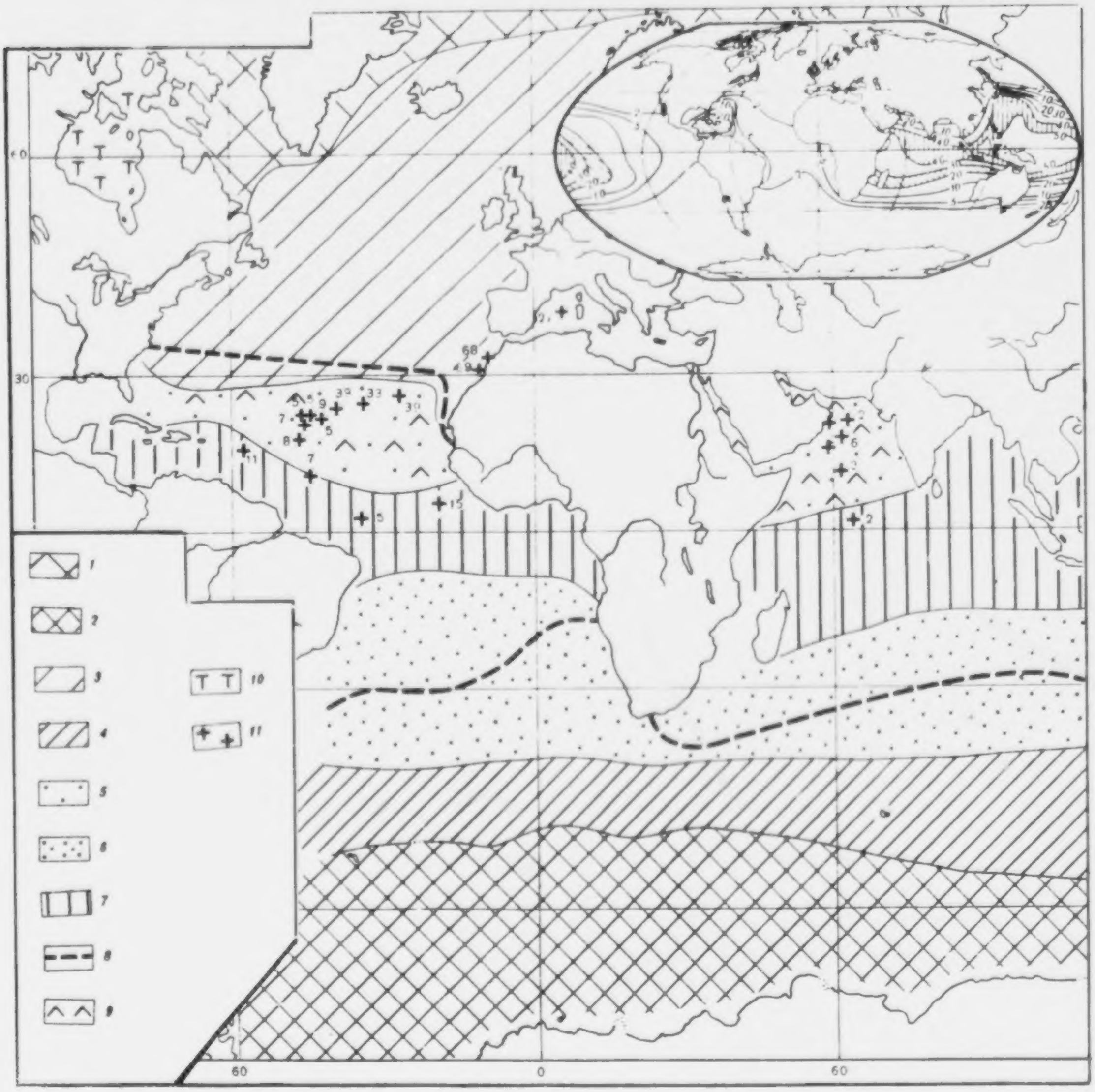


Fig. 5. Zonation of types of carbonate accumulation in the ocean. Biogenous type coccolith-foraminiferal and foraminiferal carbonates. Glacial subspecies (average water temperature below 2-3°c, Globigerina pachyderma with left spiralling and Coccolithus juxley are typical): 1 - noth, 2 - south. Moderate subspecies (including the cold subpolar part, typical are Globigerine pachyderma with right spiralling, G. inflata): 3 - north, 4 - south. Arid subspecies (subtropics and dry tropics, typical is Globinerinoides ruber): 5 - North, 6 - South. Equatorial subspecies (typical are Globorotalia tumida; G. menardii): 7 - Coral carbonates (extreme borders of coral reef distribution); 8 - Terrigenous subspecies; 9 - sediments rich in eolian carbonaceous material; 10 - sediments enriched with ice cabonaceous material (the Beaufort Sea, Hudson Bay). Other desingnations: 11 - dolomite (the Atlantic and Indian Oceans). Numbers near crosses represent % dolomite contents. On the inset: Species amount (shown by isolines) of reef-building corals in the worlds oceans, defining the type of coral sediments.

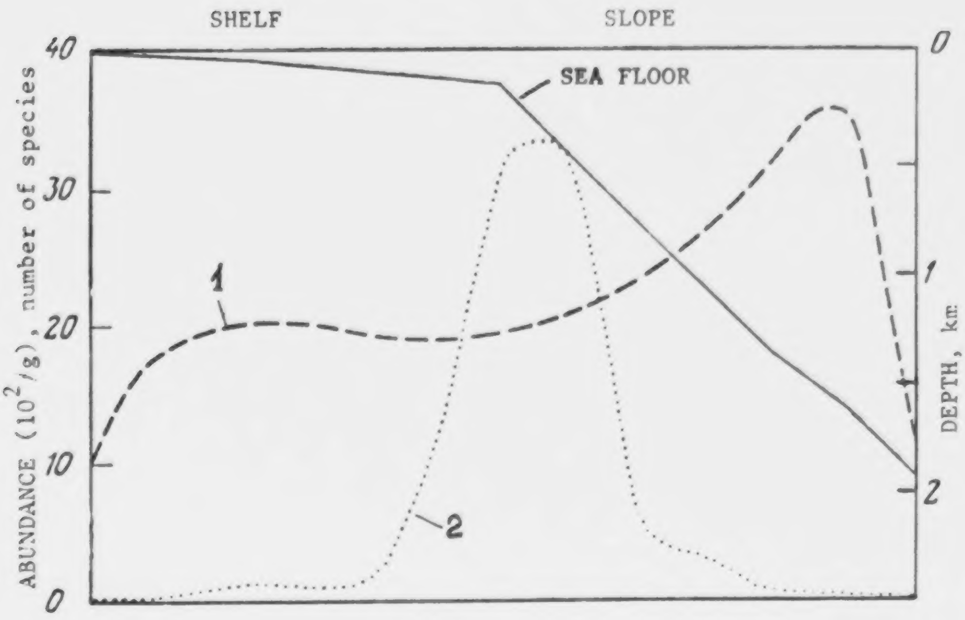


Fig. 6. Vertical and circum-continental zonation of benthic foraminifera distribution on the shelf and continental slope on the example of Central America. 1 - species variety; 2 - abundance (occurrence).

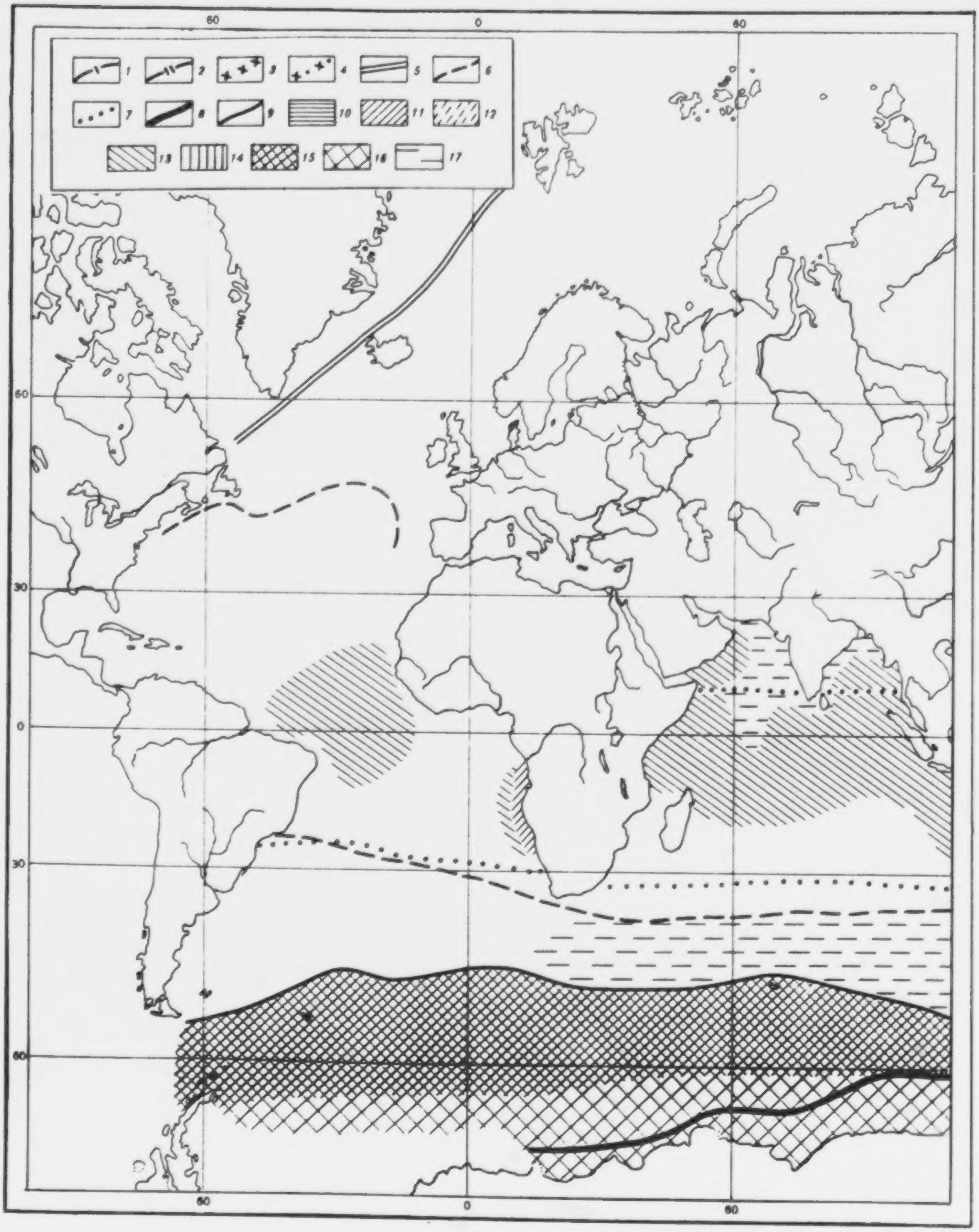


Fig.7. Zonation of types of biogenous silica accumulation in the ocean. Sediments with radiolarians: 1 - southern margin of boreal complex distribution in the Pacific Ocean; 2 - margin of distribution of the tropical complex (northern part of the Pacific Ocean); 3 - subtropical part of the tropical complex; 4 - equatorial part. The margin of complex distribution in the Atlantic and Indian oceans: 5 - northern of the boreal complex; 6 - tropical; 7 - equatorial; 8 - antarctic (ice); 9 - subantarctic (moderate). Diatoms and mainly diatoms. Complexes of diatomacean; 10 - arcto-boreal (ice of the northern hemisphere); 11 - boreal (moderate); 12 - subtropical; 13 - tropical; 14 - equatorial; 15 - subantarctic (moderate , notal, southern hemisphere); 16 - antarctic (ice); 17 - diatoms obsent.

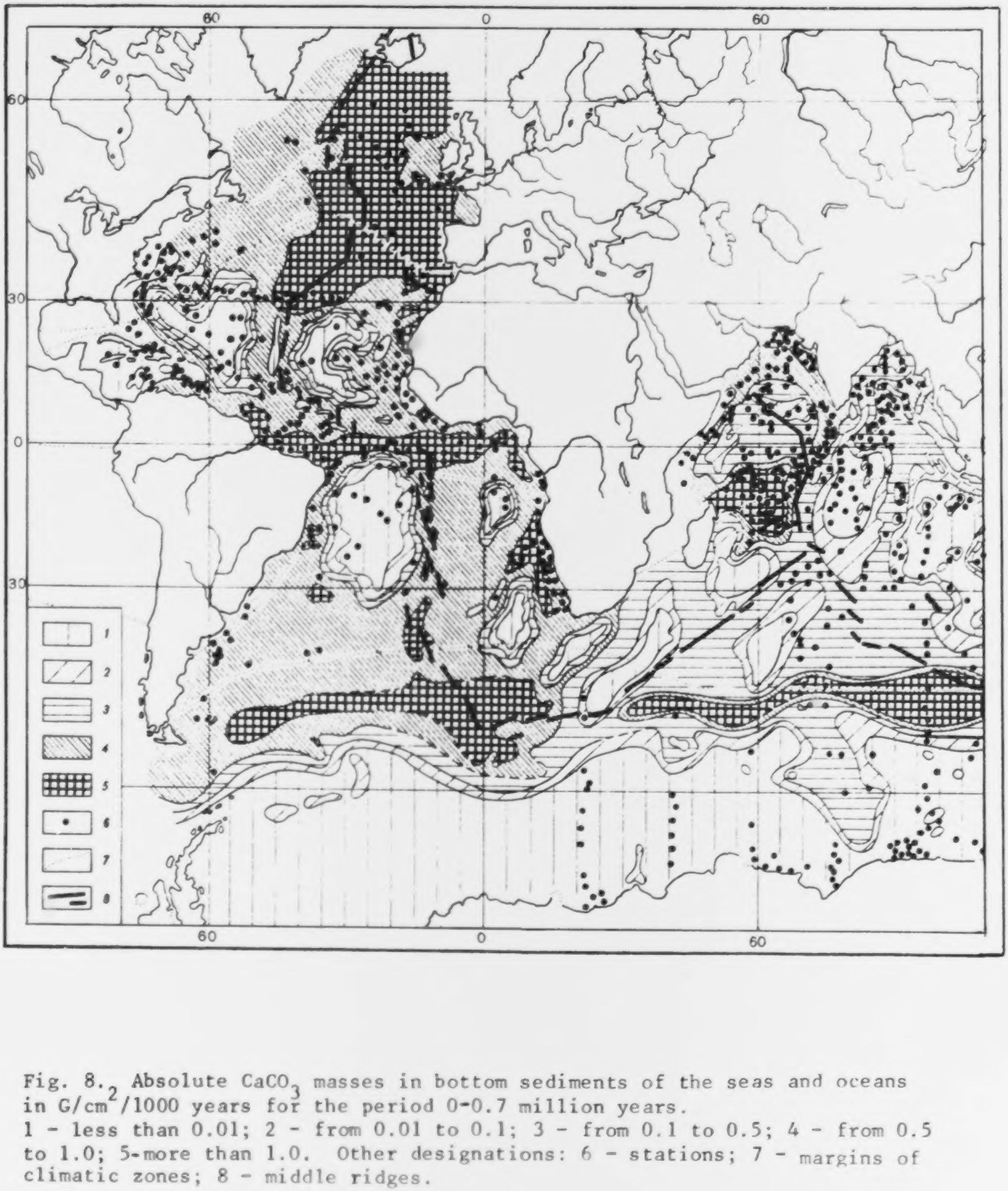

60
0
60
60
30
0
30
1
2
3
4
5
6
7
8
60
0
60

Fig. 8. Absolute $CaCO_3$ masses in bottom sediments of the seas and oceans in $G/cm^2/1000$ years for the period 0-0.7 million years.
1 - less than 0.01; 2 - from 0.01 to 0.1; 3 - from 0.1 to 0.5; 4 - from 0.5 to 1.0; 5-more than 1.0. Other designations: 6 - stations; 7 - margins of climatic zones; 8 - middle ridges.

Primary production and depth also determine the distribution of the biomass of bottom organisms, many of which play a role in the sedimentation process (mollusks, corals, crustaceans, calcareous forms etc.). As primary organic matter, the food of benthic organisms, is formed in the upper oceanic layers constituting the photosynthesis zone, at greater depths the organic matter is increasingly destroyed and consequently the nutrition available to bottom organisms is reduced, and their biomass quickly decreases.

Benthic organisms supply sedimentation mainly with carbonaceous material and we can estimate their role from absolute masses of $CaCO_3$. In accordance with the above, their greatest significance occurs at the shelf, where in a number of places sediments are largely composed of shelly material. As terrigenous and biogenic materials are delivered to bottom sediments at the same time, and as they both contribute to sediment composition, the most reliable way of estimating the biogenic contribution is by analysing absolute accumulated masses of planktonogenic or benthogenic carbonate (in grams per 1 m^2 per thousand years). In order to compute absolute masses, it is necessary to know not only the $CaCO_3$ percentage content, but also the rate of sedimentation and the sediment weight by volume (Lisitzin, 1974).

Coral-algal formations in the east Atlantic near the shores of Africa have (as compared to corresponding zones of the Indian and Pacific oceans) a very limited distribution area. For example, they are encountered in this oceanic part of the equatorial zone, which provides rather unfavourable conditions for them, near the shores of Nigeria where banks with diameters of a water depth of 1-2 km are formed. The zone inhabited by coral does not exceed 50 m. Old coral banks at depths from 47 to 88 m. have been found near the shores of Nigeria. C_{14} dating shows their age to be 5,8-6 thousand years.

The basic material of these coral structures is aragonite, which accounts for high strontium contents. For lithothamnium material, high contents of magnesian calcite are quite characteristic. In a specific deposit, the proportion of carbonaceous minerals, and their chemical composition, change as a function of the ratios of remnants of reef-building organisms. The most significant organism in reef building is the calcareous algae Khalimeda, after which, in decreasing order of importance come madrepore corals, mollusks, benthos foraminifera, echinoderms and other organisms (Lisitzin et al., 1977). Such ratios determine a significant aragonite content in coral-algal sediments.

Planktonic foraminifera occur on the shelf in insignificant amounts, just like coccolithophorids, which are concentrated in deep-water deposits. Bottom foraminifera have only a minor part in the overall $CaCO_3$ balance: only on shelves does their content exceed 5% of the total $CaCO_3$; in the pelagic zone, contents of 1-5% and even less than 1% are typical.

Thus, areas in which carbonaceous minerals are found in West Africa can be distinguished as follows: on shelves we find aragonite, magnesian calcite and calcite, and then an area of calcite, aragonite and magnesian calcite, which is soon replaced by an area of pure calcite in the pelagic direction. On the example of carbonaceous sediment distribution, one can see how important it is to consider biological data when mapping.

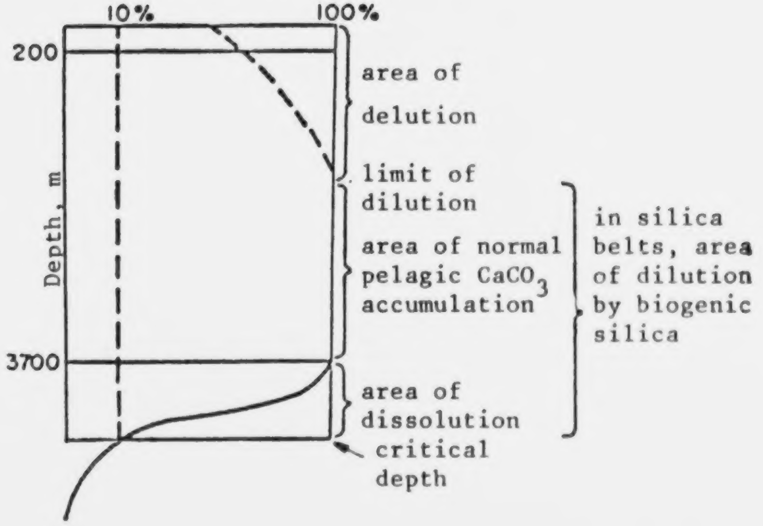
The waters of the ocean near the shores of West Africa are over-saturated with $CaCO_3$. Calcite saturation in the surface layers varies from 200-230% in arid zones to 240-270% in the equatorial humid zone. A 100% water saturation level is determined by physico-chemical conditions, and is thereby related to vertical and circum-continental zonation (fig. 9).

The depths of saturation by calcite and aragonite (100%) change as a function of latitude, as does the depth at which carbonaceous material begins to dissolve (lysocline), and the critical depth of carbonate accumulation (where $CaCO_3$ content falls to 10%), (figs. 10-12).

In the eastern part of the Atlantic Ocean, carbonaceous sediments are deposited at greater depths than anywhere else in the world, up to 5700-6000 m. in arid zones and 5300-5400 m. in equatorial humid zones. This peculiarity of sedimentation in the Atlantic Ocean is due to the fact that its abyssal waters are "doubly ventilated", by unimpeded delivery of cold water from both the Antarctic and the Arctic Ocean. In other oceans, delivery of water from the Arctic is blocked, which causes distribution, in the benthic layer, of water with a high carbon dioxide content, and hence a rise in the critical depth of one thousand metres, or some times even more (fig 9).

Vertical zonation, particularly evident in the case of carbonate accumulation, producing underwater mountains and ridges, rising from the ocean bottom above areas of abyssal non-carbonaceous clays (below the critical depth), are usually crowned with caps of white carbonaceous sediment, like snow-caps on land. The upper parts of such caps (above the critical depth for aragonite), i.e., to a depth of 2-2,2 thousand metres, are enriched with aragonite and carbonaceous material. Below the critical depth for aragonite, there is a predominance of calcite, whose content, falls rapidly as one approaches the critical depth for carbonate accumulation. Below the critical depth for calcite due to the dissolving of $CaCO_3$, abyssal non-carbonaceous clays appear. A decrease in the percentage of $CaCO_3$ content lower than 10% can be related not only to its dissolution, but also to its simultaneous dilution by terrigenous material (and in some places by siliceous as well). In pelagic ocean sections, one can estimate the position of the critical depth of carbonate (calcitic) accumulation from the 10% $CaCO_3$ isoline.

Vertical zonation of the environment leads to mineralogical differentiation and mineralogical zonation of carbonates: at depths from the surface down to 1,5-2 thousand metres aragonite can occur; high magnesian calcite can occur to depths of about three thousand metres


10%
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area of normal
pelagic $CaCO_3$
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area of
dissolution
critical
depth

Fig. 10. The geometry of $CaCO_3$ vertical distribution curves in oceanic sediments (vertical zonaliton and critical depth).

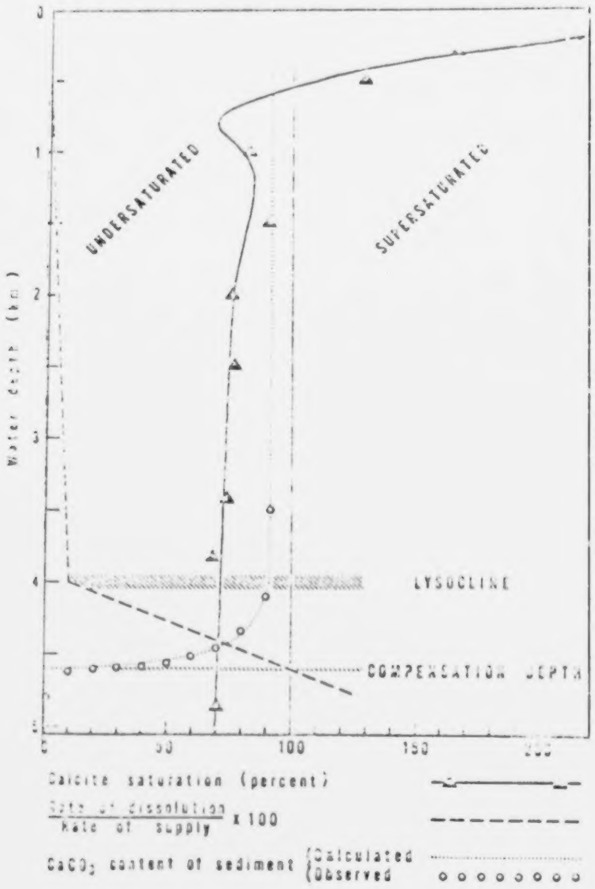


Fig. 9. Factors, influencing $CaCO_3$ distribution by depth

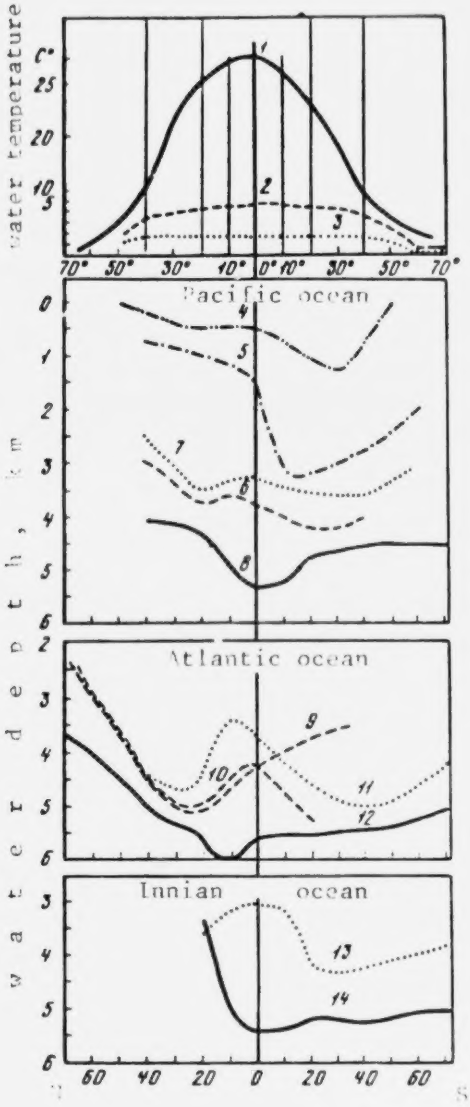


Fig. 11. Vertical zonation of $CaCO_3$ distribution in sea and ocean sediments as related to environmental characteristics by latitudinal climatic zone. Water temperature in the Pacific Ocean: 1 - surface; 2 - average suspended over a water column (surface-bottom); 3 - benthic. Indicators of carbonate accumulation by oceans: Pacific Ocean (4-8); 4 - 100% saturation depth for aragonite; 5 - 100% saturation depth for calcite in the section along 170°w longitude; 6 - lysocline; 7 -depth at which dissolution starts; 8 - critical depth; Atlantic Ocean (9 -12); 9 - lysocline, western part; 10 - lysocline, eastern part; 11 - depth at which dissolution starts; 12 - critical depth; Indian Ocean (13 - 14): 13 depth at which dissolution starts; 14 - critical depth.

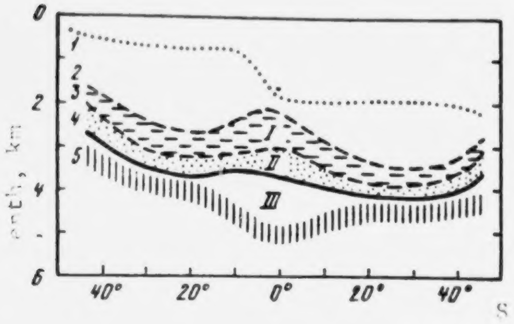


Fig. 12. Preservation of carbonaceous microfaune as a function of depth and latitude.
1 - saturation depth (for aragonite). Lysoclines (2-4): 2 - upper lysocline - F^1; 3 - middle lysocline F^2; 4 - lower lysocline F^3; 5 - critical carbonate accumulation depth ($CaCO_3$ content less than 10%). I - III deformation facies and groups of dissolution stability: I - weak deformation, stability gr. I; II -average stability gr. 2; III - high stability gr. 3-4.

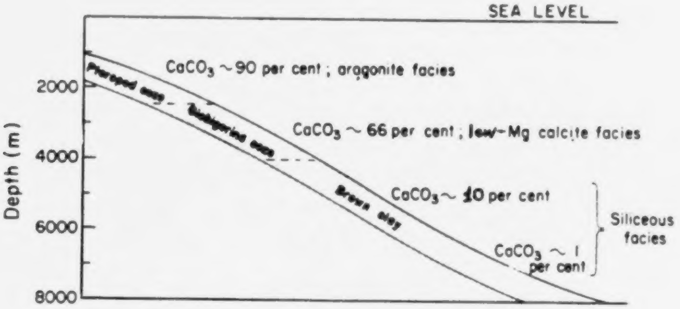

SEA LEVEL
Depth (m)
2000
4000
6000
8000
$CaCO_3$ ~ 90 per cent ; aragonite facies
$CaCO_3$ ~ 66 per cent ; low-Mg calcite facies
$CaCO_3$ ~ 10 per cent
$CaCO_3$ ~ 1 per cent
Siliceous facies
Pteropod ooze
Globigerina ooze
Brown clay

Fig. 13. Schematic $CaCO_3$ distribution in sediments in accordance with depth for the equatorial oceanic zone. Changes in $CaCO_3$ contents at genetic types with carbonate mineralogy.

while deeper than three thousand metres we find only calcite occurs (Lisitzin et al., 1977), (fig. 13). All these minerals, as noted above, are biomorphous, i.e., related to carbonaceous organisms. Critical depth is exceeded when deposits are transported gravitationally along slopes (grain fluxes, turbidity currents, etc.), with carbonates shielded from the effects of water or transported in the form of unbroken blocks (slides). This then indicates the presence of gravitites.

Vertical zonation also influences the complexity of sedimentary carbonaceous organisms: below the lysokline depth, unstable shells are dissolved and thanatocoenosis is enriched by forms resistant to dissolution (deformation of thanatocoenosis as compared to biocoenosis). Finally, this zonation influences the chemical composition of carbonaceous sediments: strontium is mainly related to aragonite, and magnesium to calcite. Hence carbonaceous strontium in equatorial and arid zones occurs mostly at depths greater than the critical depth for aragonite. High-magnesian calcite, as noted above, dissolves much higher up than low-magnesian calcite, so that low contents of strontium and magnesium are typical in the chemical composition of abyssal carbonaceous sediments, and low strontium contents are common in sediments at intermediate depths. Thus, the mineral and chemical composition of biogenic sediments on the shelf becomes more homogenous at greater depths, and finally, the set of carbonaceous minerals in the abyssal zone is limited to low-magnesian calcite.

The distribution of volcanogenic material, deposited as sediments, is determined mainly by tectonic zonation and the geological characteristics of the ocean and the area in which it is supplied. In the eastern periphery of the Atlantic Ocean, underwater volcanoes and volcanic islands are fairly characteristic (Madeira, the Canary Islands, Cape Verde, the Sierra Leone rise, the islands of Sao-Tome and Principe, Saint Helena, Tristan da Cunha and others). Their tectonic location places them all in areas of so-called inter-plate volcanism, i.e., characterised by alkaline-basaltic lava content and low explosiveness. In contrast to the volcanoes of the island arcs, these volcanoes produce very little pyroclastic material and their influence on the sedimentation process is limited to the local or regional conditions.

The main area of underwater volcanism in the world's oceans is the area of the mid-ocean ridge of the Atlantic, where extrusions of basaltic lavas in the rift valleys of the ridge are well developed, and where formation of young oceanic crust is continuing by the intrusion of fresh basalts. Volcanism is manifested mainly by the delivery of liquid products of hydrothermal activity (fig. 14), and also by the development of metalliferous sediments and crusts, or, in a few places, by the occurrence of sulphides. The basaltic ocean floor is formed by volcanism of this type and this also applies to sediments of the lower "basal" oceanic layer, enriched by material of hydrothermal origin.

In the east part of the Atlantic chemogenic sedimentation does not occur, with the exception of evaporite accumulation in some lagoons, separated from the ocean by barrier beaches.

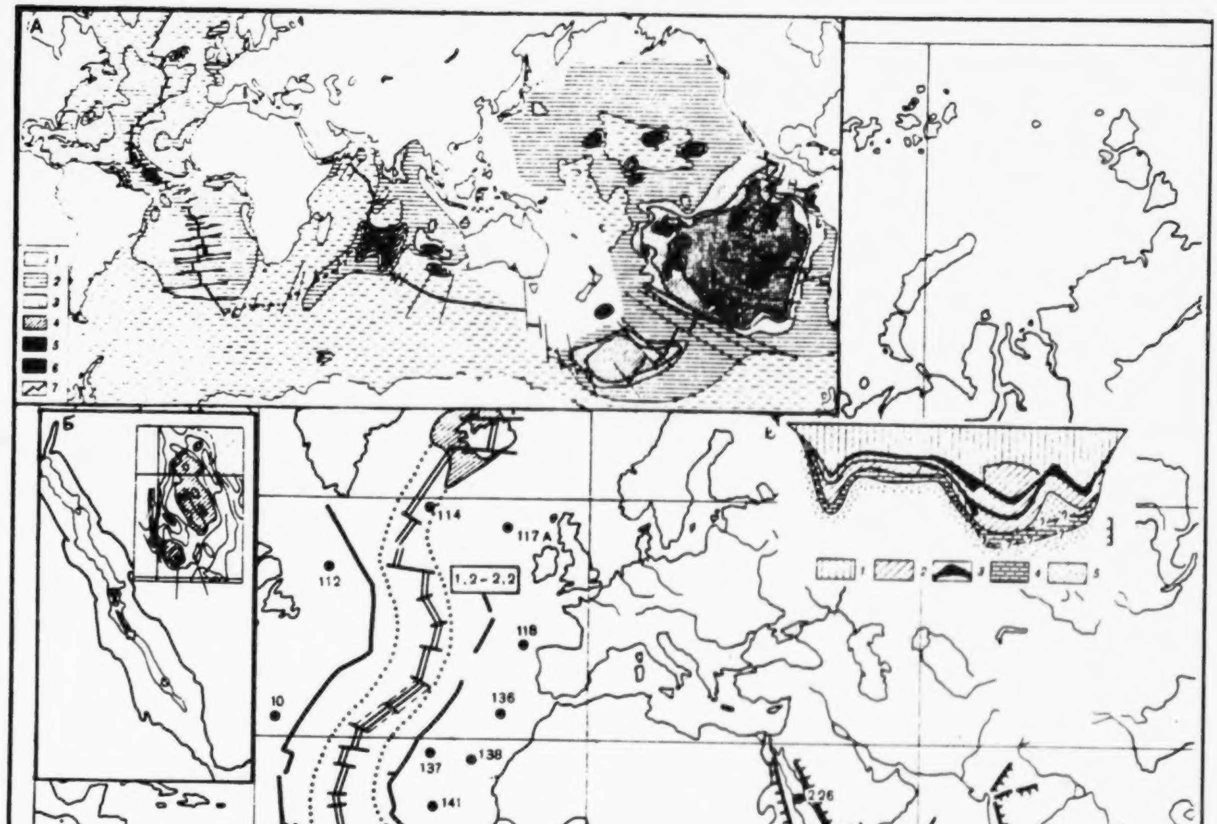

А
1
2
3
4
5
6
7
Б
В
1
2
3
4
5
114
117 A
112
1.2–2.2
118
10
136
137
138
141
226
1–1.8
2–3
P1-248
0
30
60
Г
1
2
3
20
66
2–4
1
2
3
4
5
6
7
8
9

Fig. 14. Distribution of liquid and gaseous volcanism products - metalliferous sediments in the surface layer and drilling cores of seas and oceans.
1 - middle ridges (double lines) and intersecting faults; 2 - age of basaltic bed from paleomagnetic data (in million years); 3 - boundary of Cenozoic and Mesozoic oceanic basaltic beds; 4 - main distribution areas of metalliferous sediments in the oceans (more than 10% Fe with respect to non-carbonaceous non-siliceous material); 5 - drilling cores in which metalliferous sediments were found (age of metalliferous layers shown by index); 6 - cores of bottom sediments, at some distance from ridges, in which metalliferous sediments were found; 7 - zone of problable occurrence of metalliferous sediments in surface layers; 8 - rift zones of Africa and India; 9 - rate of oceanic bottom spreading in the middle ridges zone.
A. Geochemical indicator of endogenous material delivery to sediments. Ratio of (Fe + Mn)/T : 1 - less that 10; 2 - from 10 to 15; 3 - from 15 to 20; 4 - from 20 to 25: 5 - from 25 to 100; 6 - more than 100; Other designations: 7 - middle ridges.
B. Metalliferous sediments at the bottom of the Red Sea. Positions of the main depressions with hot brines and metalliferous sediments are shown: Atlantis-II, Discovery, Chain. Shaded areas are more than 2000 m deep.
C. Metalliferous sediments of the Atlantis-II depression and facies of metalliferous sediments. Below diagram of iso-pachous lines (through 5 m): 1 - metalliferous sediment thickness more than 20 m; 2 - stations; 3 - isopachous lines. Above -cross-section of metalliferous deposit thickness and facies of matalliferous sediments: 1 - metalliferous; 2 - goethite; 3 - sulphide; 4 - carbonaceous; 5 - sea bed basalts.
D. Dependence of metalliferous sediments width zone near the East Pacific rise on the rate of ridge spreading (points - analyses).

Thus, the combination of latitudinal, vertical circum-continental and tectonic zonations defines the course of terrigenous, biogenic and volcanogenic sedimentation, as well as sediment distribution and composition laws. An understanding of these laws is very important for mapping. A number of publications on this subject have appeared recently (Lisitzin 1974, 1977 a, b, 1978, 1981. Types of bottom sediments ... 1975; Emelyanov, 1982; etc.).

The dynamics of sedimentation to the west of Africa are governed in the Atlantic Ocean by the presence of two strong systems of cold coastal currents; the Canary and the Bengal, and also by the south and north trade-wind currents.

Surface currents are observed to depths of 800-1000 m. Vortices (ringers), separated from the main currents, reach depths of 1500 m, and move at speeds of up to 25 m/second. Abyssal currents occur lower down, and close to the bottom, currents are related to the delivery of cold heavy water from the Antarctic and the Arctic ocean.

While dynamic factors (currents, waves, etc., fig. 15) are of greatest significance for sedimentary material in the shelf and pelagic zones of coastal areas, on the continental slope gravitational factors play the decisive role. It is gravitation that determines the general direction of sedimentary material transport on continental slopes from the most elevated parts to the base of the slope. Gravitational factors also determine the preparation, transportation and accumulation of sedimentary material on the slope, as well as the particular properties of this material, and its specific texture and structure (Lisitzin, 1983, 1984, 1985), (fig. 16).

For sedimentation on the shelf and continental slope, variations in the oceanic level in the geological past are especially significant. During the Mesozoic and Cenozoic periods these changes had an amplitude of up to 600-800 m. On more than one occasion, the ocean dropped globally to a level of -350 m. During the Quaternary period the oceanic level fell to 100-150 m, and estuaries and deltas, as well as most of the shelf, appeared as land, so that sedimentary material deposited here was transported to the base of the continental slope (fig. 17).

Erosion processes at the first global level of avalanche sedimentation, in river mouths, occurred simultaneously with avalanche accumulation of sedimentary material in places where it is constantly maintained - at the second level of avalanche sedimentation, near the slope base, (Lisitzin, 1984). Continental slopes still have their ancient (100-150 mln old years in some places) drainage system with numerous valleys and canyons, that have sediment-collecting cones in the upper part, transporting valleys (canyons) in the middle and the underwater debris cone at the bottom (fig. 17).

The slope base consists of separate moduls, the underwater debris cones, composed mainly of gravitites and connected by a valley with sediment-collecting cones, situated in the upper part of the slope and often extending to the shelf. Enrichment of avalanche sedimentation

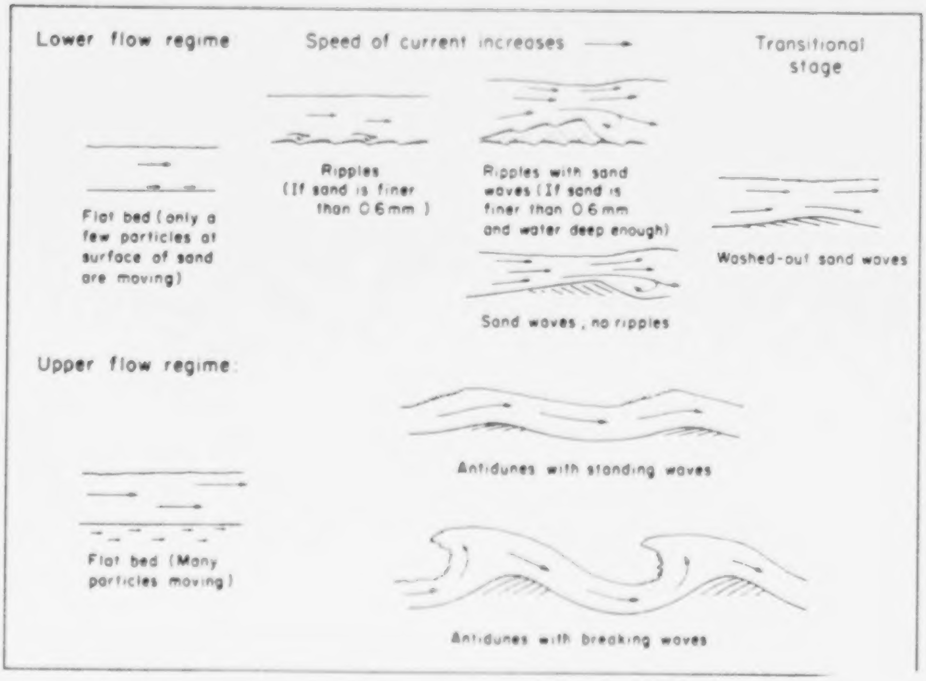

Lower flow regime
Speed of current increases
Transitional stage
Flat bed (only a few particles at surface of sand are moving)
Ripples (If sand is finer than 0.6mm)
Ripples with sand waves (If sand is finer than 0.6mm and water deep enough)
Washed-out sand waves
Sand waves, no ripples
Upper flow regime:
Antidunes with standing waves
Flat bed (Many particles moving)
Antidunes with breaking waves

Fig. 15. Characteristic forms of bottom surface microrelief depending on the current speed (speed is progressively increasing).

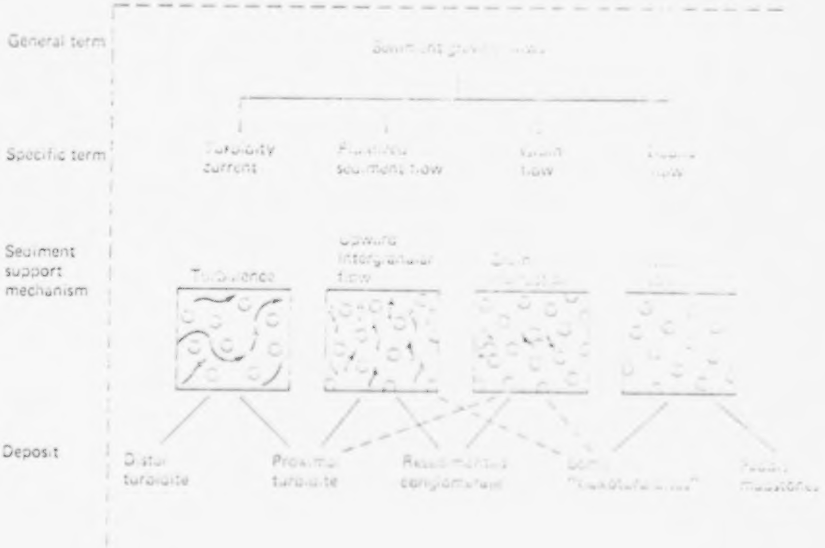

General term
Sediment gravity flows
Specific term
Turbidity current
Fluidized sediment flow
Grain flow
Debris flow
Sediment support mechanism
Turbulence
Upward intergranular flow
Grain interaction
Deposit
Distal turbidite
Proximal turbidite
Resedimented conglomerate
Some "fluxoturbidites"
Pebbly mudstones

Fig. 16. Classification of gravitational fluxes of the continent slope and their sediments.

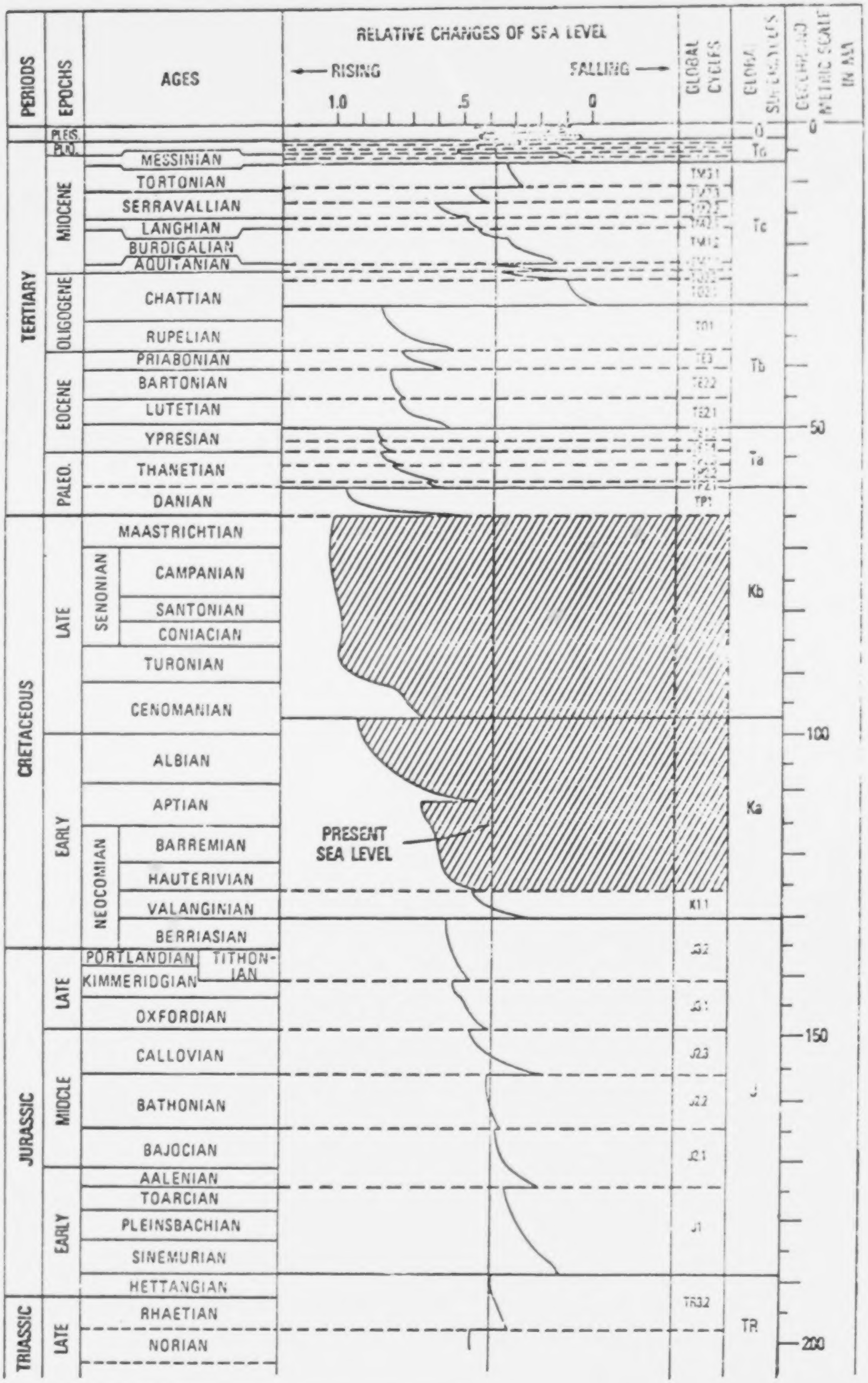


Fig. 17. Global cycles of ocean level changes during the last 200 million years. Data for the shaded area have not been published.

by sedimentary material at the second global level occurs periodically as sedimentary material at the first level, (given the present high ocean level), accumulates in river mouths (estuaries and deltas), and to a lesser extent in shelf depressions. During stages of sea-level decrease, the erosion base is transferred to the upper part of the slope and sediments break off to the slope. At least a general understanding of the processes, which govern the amount and composition of sedimentary material, and knowledge of distribution mechanisms, are necessary for proper mapping of sediments in any given region, and for assessment of the main factors contributing to the sedimentation process, which might otherwise be hidden behind the influence of numerous regional and local factors of secondary or tertiary importance. Additional information on the general principles of sedimentation can be found in a number of works (Lisitzin, 1974, 1977 a, b, 1978, 1984 a, b, et al.), and for the Atlantic ocean - in particular, in the series of monographs: Sedimentation ... 1975, Conditions ... 1971, Types ... 1975, from the coloured maps of the Atlantic Ocean (scale 1:20 mln), appended from the works Lisitzin et al. (1977), Emelyanov and Romankevich (1979), Formation ... (1978), Rocks and coarse clastic material. (1981), Emelyanov, (1975), and also in the monographs: Emery and Uchupi (1985), Geology of the East Atlantic ... (1971). For the Mediterranean Sea information can be obtained from the works: Emelyanov (1975), Emelyanov et al. (1979), Shimkus (1981), etc. Sedimentation in the western part of the Indian Ocean, adjacent to Africa, is considered in the Geological-geophysical Atlas of the Indian Ocean (1975) and many other publications.

Chapter 2. NOMENCLATURE AND CLASSIFICATION OF SEDIMENTS

Classification is the division of all sedimentary deposits into specific groups on the basis of one or several determining indicators. Nomenclature is the definition of different types of sedimentary formation, according to a system of generally accepted designations.

At the present time there is no single classification of sedimentary formations on a world-wide scale, and often not even on national levels. Thus, it is difficult to compare data collected by different scientists and at different periods of time.

To classify means to determine or distinguish certain classes or groups of sedimentary formations on the basis of actual characteristics or important indicators. It is natural that, with scientific progress, the factors determining the main features of sediments may change, as the study of sediments becomes more detailed. In addition, certain factors appear to be important in the study of industrial characteristics of sediments, while others may be more significant when studying oil-producing sediments. Hence there is no unique "correct" international classification or nomenclature, and they change with time as a function of scientific progress and requirements.

It has now become quite clear, that two groups of features are the most important for distinguishing among all sedimentary deposits (classification), and for defining their nomenclature which must reflect these properties; hence a binary system of nomenclature is proposed. Only if these two determining features - size of particles and their composition - are taken into consideration, does the classification have geological meaning. These leading features mut be determined on a quantitative basis: the size of particles forming the sediment by granulometric analysis, and their composition by mineralogical, chemical and other types of analysis, in particular the microscopic study of sediment slides.

The principles of classification and nomenclature, proposed by P.L. Bezrukov and A.P. Lisitzin (1960) about 25 years ago, and based on the quantitative characteristics of these two indicators, are now almost universally accepted. Unfortunately, this is not the case for the compilation of maps of bottom sediments. It is clear that quantitative principles, lying at the foundation of classification and nomenclature, must be reflected in cartography.

The new principles of cartographic representation of bottom sediments, using both principal indicators, were demonstrated for the first time by the author when he compiled maps of bottom sediments of the Bering Sea (Lisitzin, 1959, 1961, 1966), and later in a number of other publications. In 1969 a coloured map of Atlantic Ocean sediments was published; it was accompanied by a series of 12 special maps (maps of granulometric and material composition, bathymetric and geomorphological maps, etc.). These maps were followed by a multi-volume description of sedimentation conditions and types of bottom sediments, of suspended matter distribution and composition, and of the petrography, mineralogy and geochemistry of bottom sediments (Conditions ... 1971, Types ... 1975, Sedimentation ... 1975, Lisitzin et al., 1977, Formation ... 1978, Emelyanov and Romankevich, 1979, Indigenous ... 1981, Shimkus, 1981, Emelyanov, 1982, etc.). This ten-volume series was compiled according to a common outline under the editorship of A.P. Lisitzin. It is unique in the world literature on marine geology and will, undoubtedly, be useful to scientists working in waters off the shores of Africa. Thus, the new system for compiling maps of bottom sediments has been tested in different climatic oceanic zones, for mapping on various scales, and at different depth intervals.

Coloured maps of bottom sediments are very revealing, but their black-and-white variants may be used as well. The new method of mapping sediments received international recognition in the International Geological-geophysical Atlas of the Indian Ocean (1975). Therefore, the classification and nomenclature of sediments described below, and the new principles for sediment mapping may be recommended for application to geological studies near the shores of Africa.

We have also considered simplified classification variants, which are still based on the same two leading sedimentary features, but with determination by simplified methods (using a microscope, or even visually, in a number of cases).

In field descriptions based in the binary system, such simplified classifications are sometimes applied in conjunction with time-saving methods and standards, which make the determinations more precise. In those cases when the ship can be equipped with a microscope, classification of sediments is simplified by the preparation of transparent slides of sediments (smear slides), i.e. visual descriptions are supplemented by microscopic ones. Practice shows that, with sufficient experience, microscopical determinations (nomenclature) of sediments are usually quite accurate and change very little following analytical investigation.

Classification and nomenclature also change as a function of the scale of the mapping. As maps become more detailed, more precise weights should be used.

Adoption of this natural and realistic approach, which does not restrict scientific initiative, raises the following question - how will it be possible to compare local variants of nomenclature and classification with the universal classification of sedimentary deposits? Will geologists, working in different regions and in different countries, understand each other?

The answer is very simple: by application of a quantitative i.e., numerical basis for sediment identification according to their main features. Verbal determinations of sedimentary formations unsupported by figures, are lacking in precision, which has caused confusion for a long time, and made it impossible to compare data supplied by different authors.

Our experience shows that, by using a numerical basis, even such seemingly incomparable results as determination of the granulometric content of sediments by the "e" system (adopted in the USA, fig. 18), and the results of granulometric analysis based on the metric system (adopted in Europe, fig. 19) can be compared and transferred to other classifications.

For reliable comparison of different classifications, numerical expressions must be accepted for both determining indicators: 1 - for the granulometric composition; 2 - for the material content.

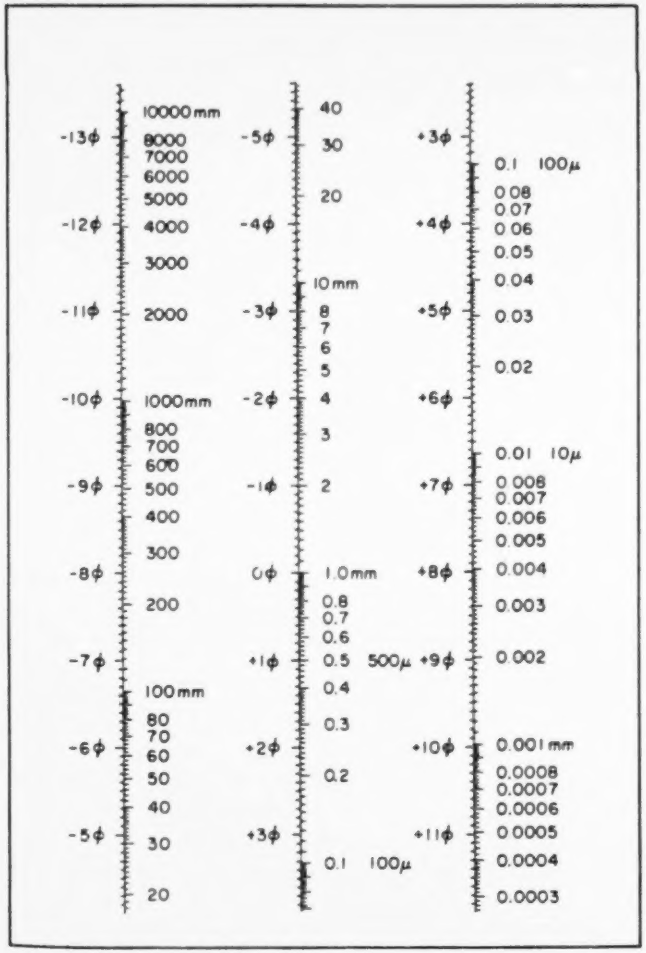
The basic principles for comparing and transferring sediments from one classification to another are given below.

The simplest classification systems, as used by scientists of the past, adopted terms from everyday speech for the definition of bottom sediments; these included sand, clay, pebble and gravel, boulders of stone. Many such terms can be found on any navigation map.

This simple way of classifying sediments was improved during the first special round-the-world geological expedition on board the H.M.S. "Challenger" in 1872-1876 (Murrey & Renard, 1891).

At the time of this expedition, it was thought that terrigenous (detrital and clayer material) plays the main role in shelf regions and biogenous material in the pelagic zone. Hemipelagic sediments, composed of both terrigenous and biogenous material, were viewed as the transition between terrigenous and pelagic. At that time, it was not yet known that most terrigenous material is accumulated not on shelves, but in river mouths, and that when the ocean level falls, which happens quite often from the geological point of view (Vail et al., 1977), this loose sedimentary material together with a considerable amount of shelf sediment, is carried to the bottom of the continental rise.

One notes that, in the classification of Murrey and Renard and its numerous modification, the determining indicator for the definition of sediments is their origin, which is why these classification systems are called genetic. In fact, the basic terms have a genetic meaning: terrigenous, i.e., originating on land; biogenous - originating from marine organisms; volcanogenic - due to volcanic activity, etc.


-13φ
-12φ
-11φ
-10φ
-9φ
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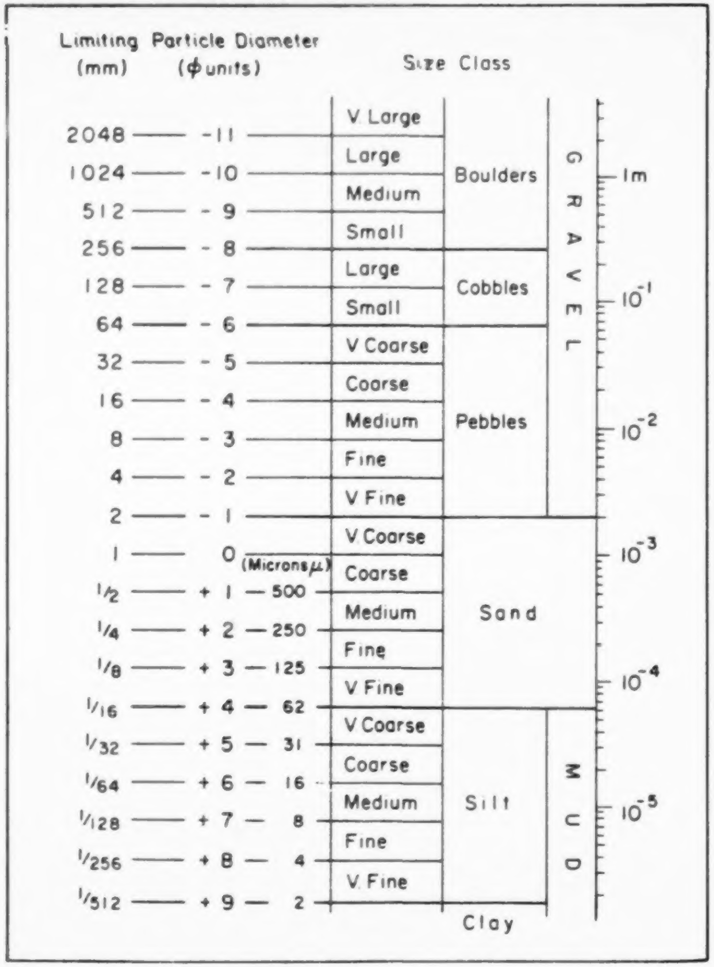
-7φ
-6φ
-5φ
10000mm
8000
7000
6000
5000
4000
3000
2000
1000mm
800
700
600
500
400
300
200
100mm
80
70
60
50
40
30
20
-5φ
-4φ
-3φ
-2φ
-1φ
0φ
+1φ
+2φ
+3φ
40
30
20
10mm
8
7
6
5
4
3
2
1.0mm
0.8
0.7
0.6
0.5 500μ
0.4
0.3
0.2
0.1 100μ
+3φ
+4φ
+5φ
+6φ
+7φ
+8φ
+9φ
+10φ
+11φ
0.1 100μ
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01 10μ
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001mm
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003

Note that millimeters are arranged on a $\log_{10}$ scale. Notice, also, that the conversion from a $\log_{10}$ scale to the φ scale can be made very simply. On the $\log_{10}$ scale find 1.0 mm and determine the distance from 1.0 to 2.0 mm. This distance equals the length of 1φ subdivision. Simply lay off this 1φ distance as a series of equal segments along the $\log_{10}$ scale in both directions from 1.0 mm.

Fig. 19. Nomogram for converting diameters of sediment particles from the metric system to the "φ" system.

Table 3-1 Standard size classes of sediment



Limiting Particle Diameter (mm)	(φ units)	(Microns μ)	Size Class		
			V Large	Boulders	GRAVEL
2048	-11				
			Large		
1024	-10				
			Medium		
512	-9				
			Small		
256	-8				
			Large	Cobbles	
128	-7				
			Small		
64	-6				
			V Coarse	Pebbles	
32	-5				
			Coarse		
16	-4				
			Medium		
8	-3				
			Fine		
4	-2				
			V Fine		
2	-1				
			V Coarse	Sand	
1	0				
			Coarse		
1/2	+1	500			
			Medium		
1/4	+2	250			
			Fine		
1/8	+3	125			
			V Fine		
1/16	+4	62			
			V Coarse	Silt	MUD
1/32	+5	31			
			Coarse		
1/64	+6	16			
			Medium		
1/128	+7	8			
			Fine		
1/256	+8	4			
			V Fine		
1/512	+9	2			
			Clay		

1m
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

Fig. 18. Classification of sediments by granulometric composition according to the "φ" system adopted in the USA.

Classifications based on granulometry and material composition are called descriptive or petrographic, as distinct from genetic. Naturally, the most successful classifications, are those with both descriptive and genetic approaches, and with all three criteria given on a quantitative basis.

Sediments of modern reservoirs are often called modern sediments, which is not quite accurate because the bottom surface is widely covered by outcrops of quaternary, tertiary and even older sediments. This is why any classification must be applicable not only to modern sediments, but also to sediments of ancient basins. This requirement is of particular importance for descriptions of long cores and cores from deep-water drilling.

The classification of marine sediments should not be replaced by classification of marine sedimentary appearance. This reservations must be made because in many classifications the physical and geographic, or facies conditions of sedimentation (i.e., pelagic, terrigenous, deep-sea, shallow-water, littoral, etc.) are emphasized to the detriment of material composition and structural features. Sediments of very similar or identical composition are thereby often placed under widely disparate classification headings. Although schemes of this kind have a certain validity, they certainly cannot fully meet the requirements of sediment petrology, with all its chemical, mineralogical and structural aspects. Of course this does not mean that classification of marine sediments should not be genetic (Bezrukov and Lisitzin, 1964).

Rational classification of sediments should satisfy one more condition: it should be applicable to sediment mapping. Mapping is an inherent part of the study of sediment genesis, and is also of great practical value. Lithological mapping on land is not applied as widely, and is usually carried out on the basis of geological maps, hence representing a special case of geological mapping.

At the same time, it ought not to be assumed that a classification can be used directly as a legend for sedimentary maps.

Finally, the classification of marine sediments must be universal, including not only all the major sediment types, but also their mixed intermediate types. This requirement inevitably makes the classification more complex than special classification schemes for individual groups of sedimentary rock.

It was considered necessary to develop such a composite classification, which would accommodate sediment characteristics on a fuller and more comprehensive scale, from the point of view not only of granulometry, but also of material-genetic composition, and which could be correlated with sedimentary rock classification. Moreover, it was obvious that the classification should reflect physical and mechanical properties to a great extent.

We show the classification scheme only for sediments of marine basins with normal salinity; therefore halogenic and some typical freshwater sediments are not included.

The classification is given in several tables.

The predominant fraction content and median diameter of sediment particles (Md) are used as the main indicators of granulometric composition.

Numerical boundaries between different sediment types are set according to the most convenient decimal subdivision (for instance, the size of sand grains is from 1.0 to 0.1 mm, that of aleurite from 0.1 to 0.01 mm, etc.

We make the following observations as explanatory notes to Table 1.

Coarse and medium sands are not always distinguishable by predominant fraction and must often be combined under the single heading of coarse and medium sands. Fine sands are always clearly defined.

We use granulometric composition to divide aleuritic sediments into coarse aleurites (0.1 - 0.05 mm), which are poorly coherent and fall apart easily when dry, and fine-aleuritic muds (0.05 - 0.01 mm), with the physical properties of typical muddy (coherent) sediments. Coarse aleurites are almost always well distinguished by the predominant fraction. The fine (0.05 - 0.01 mm) aleuritic fraction is seldom predominant. However, in fine-aleuritic muds, the two aleuritic fractions (0.1 - 0.05 mm and 0.05 - 0.01 mm) together predominate over other fractions, and the content of fine aleuritic material is greater than that of coarse aleurite. It is virtually impossible to distinguish medium aleuritic sediments.

Among the more finely dispersed sediments, a distinction is drawn between aleuritic-pelitic and pelitic muds, containing respectively from 50 to 70 and more than 70% pelitic fraction ($<$0.01 mm). When the pelitic fraction composition is dominated by clayey minerals, aleuritic-pelitic muds can be called aleuritic-clayey muds and pelitic-clayey. Such terms are not appropriate for carbonaceous and siliceous sediments, whose pelitic fraction is composed of pelitic morphous carbonaceous or opal material and not of clayey minerals. In such cases the term "ooze" is preferable, in the sense of biogenous ooze, whether aleuritic-pelitic or pelitic.

For fine clastic sediments, the table gives the median grain diameter (Md), in addition to the size of predominant particles. This characteristic is not of practical use for coarse clastic sediment.

In poorly sorted sediments the correlation between the predomant fraction and Md is often low. In such cases it is always necessary to take the sorting coefficient (S_0) into account.

Use of Md for characterisation of granulometric composition turns out to be particularly useful when dealing with analytic results not based on a decimal scale (Lisitzin, 1956).

In Table 2 it was expedient to distinguish carbonaceous sediments with massive and psephitic structures (reef limestones, shells, calcareous nodules, crust-sinters etc.), and to divide fine-grained carbonaceous sediments into clastic, various organogenic-clastic, organogenic (all-shell), chemogenic and cryptogenic. The latter includes micro-grained carbonaceous oozes, whose origins are not yet clear. All shell sediments can contain shell clusters, but they play a secondary role. Shells and organogenic-clastic shelly sediments can consist of the shells not only of mollusks, but also of some crustaceans (ostracoda, balanus). Echinoid and crinoid organogenic-clastic sediments have not yet been sufficiently studied and are distinguished provisionally. Carbonaceous algal sediments include, in particular, coccolithophorides (nanno-oozes).

The fact that the chemical composition of carbonate sediments has not been studied adequately made it necessary in some cases to combine vertical columns (percentage $CaCO_3$). For the same reason, it was not possible to isolate dolomite-rich sediments, which are sometimes encountered in recent coral-bryozoan reefs (which may be in the epigenesis stage), and also in lagoons. The different types of carbonate biogenic sediments are separated by numerous transitional types (for instance, coral-algal, coral-foraminiferal, pteropodal-foraminiferal, etc.).

Table 3 (classification of siliceous sediments) does not require any additional explanation. We note only that, as for carbonaceous sediments, the classification of siliceous sediments is based on the quantitative principle. Amorphous silica (opal) is determined chemically by treating a triturated sample with 5% sodium extract. This method gives better results than the X-ray method, and is less laborious than infra-red spectroscopy, even though it requires constant verification by standards. The different types of siliceous sediments are also interspersed with transitional types, such as radiolarian-diatomaceous oozes and diatomaceous-radiolarian oozes.

In Tables 4 and 5 (classification of manganous and ferruginaous sediments), sediments with massive and psephitic structure (ferruginous and manganous nodules, sinters, etc.) are distinguished. Ferruginous and manganous sediments include both chemogenic and clastic sediments: the high Fe content in the latter is due to the clastic part.

Table 6 provides a scheme for classifying phosphatic sediments. In contrast to the two previous schemes, the content of the main component - phosphorus - is given here in terms of P_2O_5, as accepted in works on phosphate geology. Phosphatic sediments can also be either clastic or chemogenic, and even organogenic. Phosphatic sediments of oceans have not yet been sufficiently studied, and their classification will doubtless need to be made more precise in the future.

Table 7 shows the consolidated scheme of classification of sediments of current marine basins. To avoid confusion, only the main types of sediments are included.

The first column gives the primary division into natural groups of sediments: clastic, clayey, pyroclastic, carbonaceous (calcareous), siliceous, ferruginous, glauconitic, manganous, phosphatic, enriched by organic matter. It should be noted that, although glauconitic sediments are siliceous by composition, they must undoubtedly be distinguished as a separate group, but it is still impossible to give their particular scheme of classification for lack of analytical data.

The first three groups are not subdivided in greater detail in the table. On the basis of predominant mineral content, we can distinguish a number of sediment types among them: for instance, among clastic sediments - quartz, feldspathic, pyroxene, magnetite, etc.; among pyroclastic - differently composed tufogenic, tuffitic, etc., among clayey - hydromic, montmorillonitic, etc. In addition, the sediments of the first three groups can be subdivided according to their content of certain important accessory minerals (for instance, cassiteritic sands, monozitic sands, etc.).

In other groups we distinguish subgroups of organogenic, organogenic-clastic (only for siliceous and carbonaceous), clastic and chemogenic sediments (including those formed during diagenesis), as well as individual types of sediments; for instance, among siliceous sediments - sponges, diatomaceous, etc.; among carbonaceous - shelly, coral, etc.

The remaining columns of the table show sediment groups by granulometric content.

From Table 7 one can see (+), for example, that diatomic sediments may be present as diatomic sands (seldom), diatomic aleuritic and clayey muds; organogenic-clastic coral sediments as coral gravels and pebbles, coral sands, aleuritic muds; and so on.

In conclusion a few words must be said about "abyssal red clay". It is not distinguished in these tables because red clays are rather varied in terms of granulometry and basic material composition, and in addition, they differ to a very small degree from other shallow-water uncarbonaceous clayey muds of the oxidized sediment zone. The differences consist mainly in the content of a number of dispersed elements, of cosmic material, organic remains and also in a generally higher content of ferric and manganese oxides. However, as a specific facies type of sediment, characteristic of great ocean depths, red clays must certainly be distinguished and can be shown by a special sign on bottom sediment maps. One should consider not only the lithological and faunistic characteristics of sediments of this type, but also their thickness, because in marginal areas of the ocean, brown clayey muds, with the features of red clay, often form only the thin surface layer of sediments or are interlayed with compositionally similar grey muds of the restoration zone. Other facies sediment groups can also be distinguished on maps, for instance, such sediments as: glacial, iceberg, eolian, bottom slides, suspended fluxes, etc. As the goal of this work is lithological classification of marine sediments, we shall not consider this question in detail.

Based on a study of many thousands of samples, certain numerical limits in the group of carbonaceous sediments were refined, as their main part usually contains more than 50% $CaCO_3$. Sediments containing from 30 to 70% $CaCO_3$ are usually marlaceous, and sediments containing more than 70% $CaCO_3$ are termed strictly calcareous.

Sediments containing more than 70% clastic and clayey material are included in the clastic group. Their further subdivision is made according to predominant fraction (i.e., the fraction, which accounts for more than 50% of the sediment). Sediments usually have three fractions - sandy, aleuritic and pelitic, rarely joined by a fourth-psephitic (coarse clastic). If the sandy fraction (more than 50%) predominates in the sediment, then a further determination of granulometric type is done on the basis of proportions of sandy fractions. Mass analysis usually distinguishes three sandy fractions: coarse (1-0.5 mm), medium (0.5 -0.25 mm) and fine (0.25 - 0.1 mm). If the predominant fraction in the sand is fine, according to the analysis, then it is called fine sand. For detailed work, it is more convenient to use classification and mapping based on predominant fractions, rather than median diameters and sorting coefficients. The best expression of sedimentation zonation and facies conditions is found in material-genetic sediment types. Each type is characterized by a generally raher limited number of sediments, with distinct material and granulometric composition, physico-mechanical and other properties, special microflora and microfauna, and specific mineral composition (clastic, biogenic and authigenic minerals). Sediment material composition is closely connected with genesis. For mapping on a small scale (less than 1:5 mln) we distinguish the following material-genetic types of sediments (Lisitzin, 1974):

I. Terrigenous (clastic and clayey)

    Icebergous (glacial)
    Sediments beyond the iceberg zone (icy and others)

II. Biogenous (organogenic)

  Carbonaceous

    Planktonogenic

      Foraminiferal, nanno-foraminiferal and pteropoda-foraminiferal
      Nanno and foraminiferal-nanno
      Pteropodal and foraminiferal-pteropodal
      (the predominant sedimentary material is indicated at the end of the definition)

  Benthogenic

    Coral (coral-algal)
    Foraminiferal
    Shelly
    Bryozoan

Barnacle sediments and those composed of the remains of calcareous worm forms
Composed of the remains of echinoderms (echinoidal)

Siliceous

Diatomaceous
Radiolarian and radiolarian-diatomaceous
Siliceous sponges (spiculae)
Mixed siliceous-carbonaceous

III. Authigenous (diagenetic, chemogenic) iron-manganese nodules, phosphorites, chamosite, glauconite, zeolites

IV. Volcanogenic, volcano-clastic and rich in pyroclastic material

V. Polygenic

Further subdivisions within these material-genetic types are made, as noted above, on the basis of analytic data about granulometric and material composition (by predominant granulometric fractions and predominant material components).

Conventional signs on maps, and the level of detail of classification schemes, naturally change as a function of the detail of the study and the mapping scale. When studying and mapping relatively small bottom areas, subject to fairly uniform climatic and bathymetric conditions, it is necessary to make the classification scheme more detailed, searching out even more detailed defining indicators of sediments, i.e., refining the "resolution capacity" of the classification scheme and maps. Otherwise enormous map areas would be shown as covered with homogeneous sediments, which never happens in nature.

Just as microscope magnification is chose to suit the aims of a study, so too the classification scheme and the associated sediment map legend must be as a function of the tasks set out for the work at hand. The coarsest categories (material-genetic types) are preserved, but within each, one can distinguish numerous subtypes, and even finer local subdivisions. For instance, fields of biogenous foraminiferal sediments can be subdivided into different varieties by predominant planktonic or benthic forms, natural associations or indicator species, dominant species), one can refine the study of granulometric composition of the specific mineral composition of carbonaceous and terrigenous parts, of authigenous minerals, chemical composition, etc.

The unification of different classification schemes has now been greatly simplified due to deep-sea drilling work aboard "Glomar Challenger" and "JOIDES Resolution". This undertaking required participation by scientists from many countries in the study of the same core, and gradually a single classification was worked out, on a binary quantitative basis, like the classification of Bezrukov and Lisitzin. It subdivides sedimentary formations by the two most significant indicators, expressed numerically: granulometric composition and material content (fig. 20).

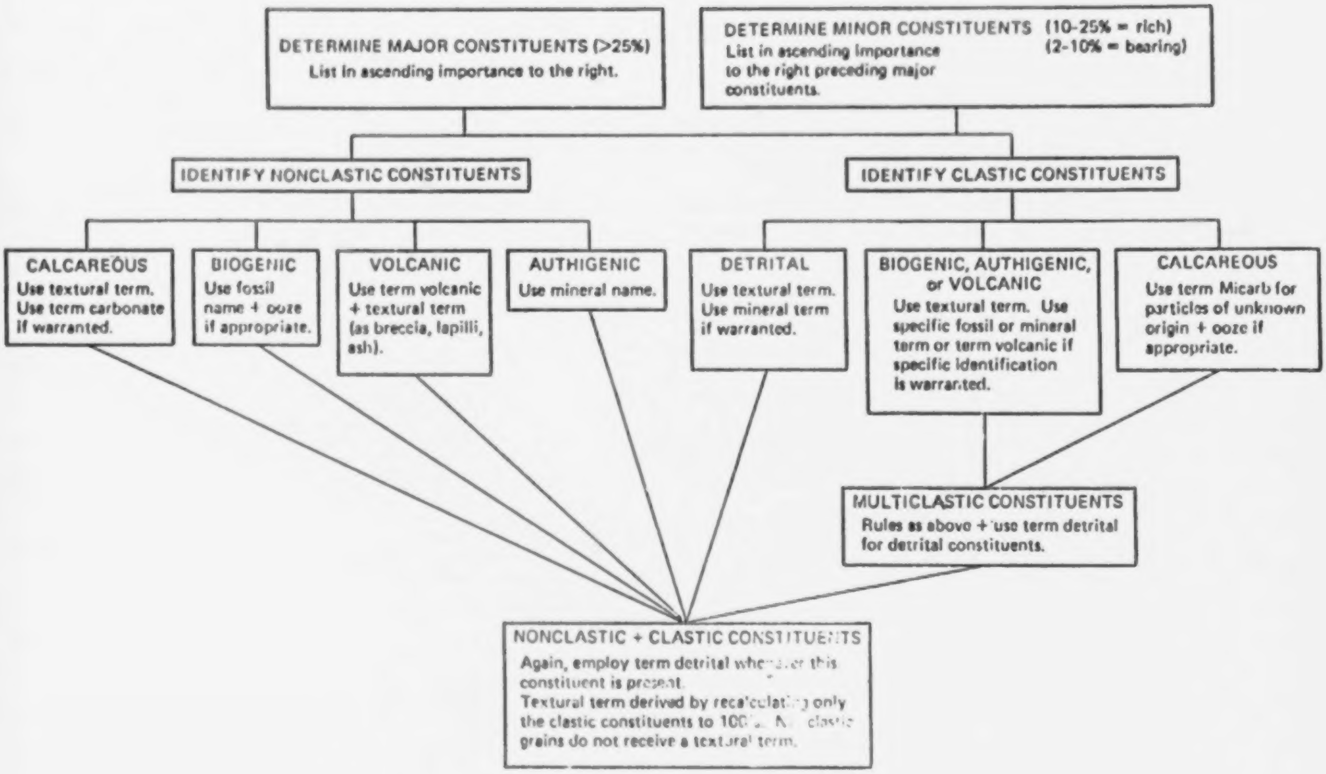

DETERMINE MAJOR CONSTITUENTS (>25%)
List in ascending importance to the right.
DETERMINE MINOR CONSTITUENTS (10-25% = rich) (2-10% = bearing)
List in ascending importance to the right preceding major constituents.
IDENTIFY NONCLASTIC CONSTITUENTS
IDENTIFY CLASTIC CONSTITUENTS
CALCAREOUS
Use textural term. Use term carbonate if warranted.
BIOGENIC
Use fossil name + ooze if appropriate.
VOLCANIC
Use term volcanic + textural term (as breccia, lapilli, ash).
AUTHIGENIC
Use mineral name.
DETRITAL
Use textural term. Use mineral term if warranted.
BIOGENIC, AUTHIGENIC, or VOLCANIC
Use textural term. Use specific fossil or mineral term or term volcanic if specific identification is warranted.
CALCAREOUS
Use term Micarb for particles of unknown origin + ooze if appropriate.
MULTICLASTIC CONSTITUENTS
Rules as above + use term detrital for detrital constituents.
NONCLASTIC + CLASTIC CONSTITUENTS
Again, employ term detrital whenever this constituent is present.
Textural term derived by recalculating only the clastic constituents to 100%. Nonclastic grains do not receive a textural term.

Fig. 20. Classification and nomenclature of sediments adopted in deep-sea drilling, leg 1 - 37 (from the upper level to lower ones).

The classification adopted as of "Glomar Challenger" leg 38 is basically descriptive, in that it takes granulometric and material composition into consideration, but it involves genetic aspects as well. Determination of sediment types can be done on board the ship, i.e., before granulometric and material content analyses. It is then based mainly on descriptions of smear-slides. This methodology was widely used for the first time about 20 years ago by A.P. Lisitzin and B.P. Petelin (1956) during a leg of R/V "Vityaz" in 1949-1950.

Under large-scale working conditions, with good training and constant usage of a reference collection of slides (standards for granulometric and material composition), the determination accuracy of the principal defining sediment components in preparations appears to be close to analytical accuracy, and is quite satisfactory for practical purposes.

If it is impossible to use a microscope in the field because the ship is too small, microscope description of smear-slides must shortly follow sample collection in a shore laboratory and must precede analytical investigation.

This procedure makes it possible to change quickly the course of the study, to impose a finer network in places with complicated sedimentation, or a coarser one in places with uniform distribution. The validity of the following principle has now been demonstrated: "Sediments have not been studied, if they have not been examined on smear-slides and microsections!". The study of sedimentary preparations through a microscope is a highly effective and time-saving-method.

We give below the principles of sediment nomenclature on the basis of microscopic investigation, which is then corrected by analytic data, as worked out by many scientists and generalised during deep-sea work.

Establishing the rank of constituent components

A quantitative indicator is used to distinguish between 2 ranks of sediment-forming constituents: principal and secondary.

A. Principal (sedimentary) constituents

1. The sediment takes its name from the principal constituents, present in amounts exceeding 25% (earlier the cut-off was 30%, which is not significantly different).

2. Where more than one principal constituent is present, the one in greatest abundance is placed farthest to the right, with the others listed leftwards in decreasing order.

3. When two or more principal constituents are present in a sediment, class divisions are based on 25% intervals, for example:

% Zeolites	% Nannofossils	Name
0-25	75-100	Nanno ooze
25-50	50-75	Zeolitic nanno ooze
50-75	25-50	Nanno-zeolitite
75-100	0-25	Zeolitite

B. Secondary constituents (content less than 25%)

1. Constituents present in amounts from 10 to 25% are added to the sediment name with the suffix "-enriched".

2. Constituents present in amounts from 2 to 10% are added to the sediment name with the suffix "-bearing". Example: a sediment containing according to smear-slide data, 50% nannofossils, 40% radiolarians and 10% zeolites is called a zeolite-bearing rad nanno ooze.

Rules for naming biogenic constituents

A. The term "nannofossil" is applied only to calcareous shells of coccolithophorids and discoasters.

B. The contractions nanno for nannofossil, foram for foraminifera, rad for radiolarian, and spicule for sponge spiculae may be used in the sediment name.

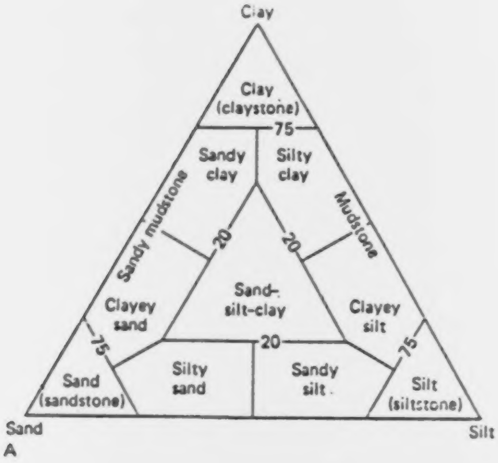
C. For biogenic sediments, the term "ooze" follows the name of the taxonomic group that dominates the sedimentary composition.

D. The term "chalk" is used for semilithified carbonate ooze and limestone carbonate ooze.

E. Semilithified diatom and rad oozes are called "diatomites" and "radiolarites", respectively. Lithified siliceous oozes are called "chert" and carbonaceous sediments - marls or limestones depending on $CaCO_3$ and clayey material content.

Rules for naming clastic sediments

A. Clastic constituents, whether terrigenous, volcanic, biogenic or authigenic, are given structural designations. When detrital grains (for example, terrigenous) are the sole clastic constituent of a sediment, then they are named in accordance with Shepard's triangle diagram (Shephard, 1954), (Fig. 21). When biogenic or authigenic grains occur the sediment, in addition to terrigenous grains, the biogenic or authigenic material is not given a granulometric designation. Since non-terrigenous fractions are present in such a sediment, the name of its clast fraction should be preceded by "terrigenous". For example,


Clay
Clay (claystone)
75
Sandy clay
Silty clay
Sandy mudstone
Mudstone
20
20
Sand-silt-clay
Clayey sand
Clayey silt
20
75
75
Sand (sandstone)
Silty sand
Sandy silt
Silt (siltstone)
Sand
Silt
A

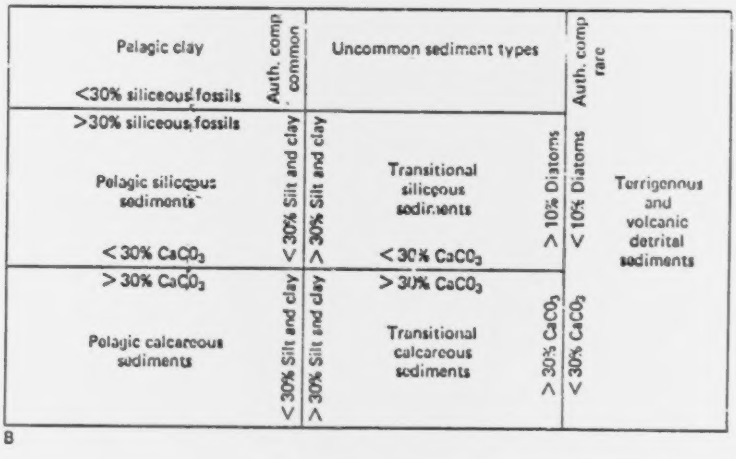

Pelagic clay
<30% siliceous fossils
Auth. comp common
Uncommon sediment types
Auth. comp rare
>30% siliceous fossils
Pelagic siliceous sediments
<30% CaCO3
< 30% Silt and clay
> 30% Silt and clay
Transitional siliceous sediments
< 30% CaCO3
> 10% Diatoms
< 10% Diatoms
Terrigenous and volcanic detrital sediments
> 30% CaCO3
< 30% Silt and clay
> 30% Silt and clay
> 30% CaCO3
Pelagic calcareous sediments
Transitional calcareous sediments
> 30% CaCO3
< 30% CaCO3
B

Fig. 21. A The triangle diagram by Shepard for classification of granulometric composition by ratios of fractions of sand, silt and pelite.

Fig. 21. B Sediments classification in deep-sea drilling cores adopted as at R/V "Glomar Challenger".

consider a sediment with 40% foraminifera and 60% terrigenous material, and with the clastic material appearing as 40% pelitic and 20% silt fraction, which gives 67% pelite and 33% silt of that material. The proper name of such a sediment is foram terrigenous silty clay.

Complete designation of a sediment, based on both material and granulometric composition, gives the material composition in the first place and the granulometric in the second.

The more detailed the classification and nomenclature, and the greater the number of constituents considered, the longer and wordier the sediment type designations. It is natural that very long and verbose designations are not readily accepted, and cannot be widely used in practice. Therefore, abbreviations are often used, and if the data are processed by computer, names are replaced by numerical codes.

In a number of cases verbose descriptions are replaced by shorter designations, reflecting a whole set of sedimentary deposit features. For example, the terms zechstein sandstones or shales, jurassic black clays, etc., which were already in use in the last century, in fact stand for a complicated set of special definitions.

Table 1. Classification of marine clastic sediments by granulometric compositions

Sediment groups	Sediments		Size of predominant particles, mm	Mean particle diameter Md (mm)
1	2		3	4
Coarse-clastic sediments (psophites)	Cobbles		1000	
	Boulders	coarse	1000-500	
		medium	500-250	
		fine	250-100	
	Pebbles*	coarse	100-50	
		medium	50-25	
		fine	25-10	
	Gravels**	coarse	10-5	
		medium	5-2.5	
		fine	2.5-1.0	
Sandy sediments (psammites)	Sands	coarse	1.0-0.5	1000-500
		medium	0.5-0.25	500-250
		fine	0.25-0.1	250-100
Aleuritic sediments (aleurites)	Coarse aleurites		0.1-0.05	100-50
	Fine-aleuritic muds		0.1-0.01	50-10
Pelitic (clayey) sediments (pelites)	Aleuritic-pelitic muds		0.01 (50-70%)	10-7
	Pelitic muds		0.01 (70%)	7

* Rock debris if fragments are angular.

** Gruss if fragments are angular.

Table 2. Classification of marine carbonate sediments

Texture 1	50% $CaCO_3$ 2	50-30% $CaCO_3$ 3	30-10% $CaCO_3$ 4	<10% $CaCO_3$ 5
Massive	Reef limestones: coral, bryozoan and intermediate; cemented shells; calcareous crusts (sinters)			
Psephitic	Shells; calcareous nodules; concretions of reef limestones; calcareous boulders; pebbles; rock debris	Shelly-boulder-pebble-gravel sediments Boulder-pebble-gravel sediments with limestone debris or concretions. Calcareous bioconglomerates		Boulders, pebbles gravels
Psammitic	Calcareous clastic sands. Calcareous organogenic-clastic sands: shelly, coral, bryozoan, lithothamnion, coralline and intermediate Oolitic sands	Calcareous sands	Low-carbonate clastic sands. Low-carbonate organogenic-clastic sands: shelly, coral, bryozoan, lithothamnion, coralline, echinoidal, crinoidal, and intermediate. Low-carbonate organogenic, whole-foraminiferal sands. Low-carbonate chemogenic, oolitic sands	Sands
Aleuritic	Aleurites and aleuritic oozes, calcareous, clastic.		Aleurites and aleuritic muds; low-carbonate, clastic	Coarse aleurites and fine aleuritic muds
	Aleurites and aleuritic oozes, calcareous, organogenic-clastic: shelly, coral, bryozoan, algal and intermediate		Aleurites and aleuritic muds; low-carbonate, organogenic, clastic	Coarse aleurites and fine aleuritic muds
	Aleurites and aleuritic oozes, calcareous, organogenic, whole-shell foraminiferal, pteropodal, and intermediate		Aleurites and aleuritic muds; low-carbonate, whole shell	
	Aleurites and aleuritic oozes; calcareous, chemogenic (oolites, etc.)		Aleurites and aleuritic muds; low-carbonate, chemogenic	
Pelitic	Calcareous organogenic-clastic, chemogenic and cryptogenic pelitomorphic oozes	Calcareous aleuritic-pelitic and pelitic organogenic-clastic, chemogenic and cryptomorphic oozes. (marls)	Aleuritic-pelitic and pelitic low-carbonate organogenic-clastic chemogenic and cryptomorphic muds	Aleuritic-pelitic and pelitic muds

Table 3. Classification of marine siliceous sediments

Texture	50% authigenous silica	50-30% authigenous silica	30-10% authigenous silica	< 10% authigenous silica
1	2	3	4	5
Psammitic	siliceous sponge sands		siliceous sands: sponge, diatomaceous	sands
Aleuritic	none	none	coarse low-silica aleurites: sponge, diatomaceous	coarse aleurites
			fine aleuritic low-silica muds: diatomaceous, radiolarian	fine-aleuritic muds
	none	none		
Pelitic	none	aleuritic-pelitic siliceous oozes: diatomaceous, radiolarian	aleuritic-pelitic low-silica muds: diatomaceous, radiolarian	aleuritic-pelitic muds
	siliceous diatom oozes	pelitic-siliceous oozes: diatomaceous, radiolarian	pelitic low-silica muds: diatomaceous, radiolarian	pelitic muds

Table 4. Classification of ferruginous marine sediments

Texture	30% Fe	30-20% Fe	20-10% Fe	10-5% Fe	< 5% Fe
Massive	sinter iron ores	high-ferruginous sinters (crusts)	ferruginous sinters (crusts)	low-ferruginous sinters (crusts)	pebble and gravel
		Pebbles and gravels from ferruginous rocks			
Psephitic	nodulous iron ores	high-ferruginous nodules	ferruginous nodules	low-ferruginous nodules	various non-ferruginous nodules
Psammitic	sandy iron ores	high-ferruginous sands	ferruginous sands	low-ferruginous sands	sands
Aleuritic		high-ferruginous aleurites	ferruginous aleurites	low-ferruginous aleurites and aleuritic muds	coarse aleurites and fine-aleuritic muds
Pelitic	none	none	none	low-ferruginous aleuritic-pelitic	aleuritic-pelitic and pelitic muds

Table 5. Classification of manganous marine sediments

Texture	10% Mn	10-5% Mn	5-0.2% Mn	< 0.2% Mn
Massive	high-manganous crusts	manganous crusts	low-manganous crusts	
Psephitic	high-manganous nodules	manganous nodules	low-manganous nodules	various non-manganous nodules
Psammitic	none	manganous sands	low-manganous sands	sands
Aleuritic	none	manganous aleurites	low-manganous aleurites and aleuritic muds	coarse aleurites and fine aleuritic muds
Pelitic	none	none	low-manganous aleuritic-pelitic and pelitic muds	aleuritic-pelitic and pelitic muds

Table 6. Classification of phosphatic marine sediments

Texture	10% P_2O_5	10-0.5% P_2O_5	$<$0.5% P_2O_5
Psephitic	phosphoritic nodules	low-phosphatic nodules, pebbles and gravels	various non-phosphatic nodules
	phosphatic pebbles and gravels		pebbles, gravels
Psammitic	phosphoritic sands	low-phosphatic sands	sands
Aleuritic	none	low-phosphatic aleurites and aleuritic muds	coarse aleurites and fine-aleuritic muds
Pelitic	none	low-phosphatic aleuritic-clayey and clayey muds	aleuritic-clayey and clayey muds

Table 7. Overall classification scheme for sediments of modern marine basins

Groups and types of sediments by material-genetic composition	Groups of sediments by granulometric composition				
	Massive	Coarse-clastic	Sandy	Aleuritic	Pelitic
1	2	3	4	5	6
1. Clastic (silicate)	-	+	+	+	+
2. Clayey	-	-	-	-	-
3. Pyroclastic	-	+	+	+	+
4. Siliceous (>10% SiO_2 authigenous)					
a) organogenic:					
sponge	-	-	+	+	-
diatomaceous	-	-	+	+	+
radiolarian	-	-	-	+	+
b) chemogenic	-	-	-	-	?
5. Carbonaceous (>10% $CaCO_3$)					
a) clastic	-	+	+	+	+
b) organogenic-clastic:					
shells	-	+	+	+	+
coral and bryozoan	-	+	+	+	+
algal	-	+	+	+	+
c) organogenic-whole shell:					
shells	-	+	+	+	-
foraminiferal	-	-	+	+	-
pteropodes	-	-	+	+	-
coccolithic	-	-	-	+	+
d) organogenic refogenic:					
coral	+	+	-	-	-
bryozoan	+	+	-	-	-
algal	+	+	-	-	-
e) chemogenic	+	+	+	+	+
f) cryptogenic					+

Table 7. (continued)

1	2	3	4	5	6
6. Ferruginous ($>$5% Fe)					
a) clastic	-	+	+	+	+
b) chemogenic	+	+	+	+	+
7. Glauconitic ($>$10% glauconite)					
a) clastic	-	-	+	+	-
b) chemogenic	-	-	+	+	-
8. Manganous ($>$0.2% Mn)					
a) clastic	-	-	+	+	+
b) chemogenic	-	+	+	+	+
9. Phosphatic ($>$0.5% P_2O_5)					
a) clastic	-	+	+	+	+
b) chemogenic	-	+	+	+	-
10. Rich in organic matter ($>$10%)	-	?	+	+	+

Chapter 3. MAPPING BOTTOM SEDIMENTS

1. General Principles

The two-dimensional approach to classification and nomenclature, centred around the two major indicators of granulometry and material composition on a strictly quantitative basis, must be maintained during sediment mapping. It is important to show these defining sediment indicators on maps, without omitting their quantitative expression, and all the fine transitions and combinations. This can be done with the system of bottom sediment maping, developed by the author and in use in the USSR (Lisitzin, 1974, 1978).

The two indicators are plotted on maps in different ways: granulometric composition by shading and material composition by colour. The richness of the colouring is proportional to the content; the more abundant a component, the denser the colour. The colour range is standardised. For $CaCO_3$ the conventional colouring is blue, for siliceous sediments - green, for ferruginous - rust-brown, for manganesian - violet, for organic matter - dark-grey. Various types of compositionally mixed sediments, which are common in nature, are shown by alternating stripes, and the density of each colour's stripes corresponds to the quantitative content of the main components ($CaCO_3$, silica, Fe, Mn or organic C). Separate symbols are used to show typical authigenous minerals, nodules, organic remains, etc.

The logic of the sedimentation process demands that sediment maps display bottom relief, as one of the main factors in this process. The relief is shown by isobathic lines, with frequency chosen as a function of the map's scale.

The principles of scientific study, which must govern proper compilation of bottom sediment maps, require that conditions on the adjoining land, as the source of clastic material, be shown as well. Maps on which the land is shown as a blank area or just schematically, are very impoverished. It is recommended that land areas of maps show the relief, elements of the river network with fluid and solid run-off figures in river mouths, deserts and steppes, as sources of eolian material, their wind roses, and drainless areas. The major features of the oceanic environment must also be taken into account: currents, biological productivity, distribution and composition of planktonic and benthic organisms, and in volcanic regions - tephra effects and delivery of hydrothermal matter.

In short, all sources of sedimentary material must be shown, as well as its transportation and transformation modes.

The modern bottom sediments map represents a synthesis of a whole range of specific preparatory maps, refleting the distribution of the major indicators of granulometric and material composition.

There are two ways of compiling maps of bottom sediment types.

The first consists in distinguishing sediment types on the basis of description or analysis, and then plotting them on the map, where type distribution areas are determined and delineated by borders as data are accumulated. As results from new stations become available, the map becomes more detailed.

The author believes this approach to be incorrect, as it does not reveal what is most important in the sedimentation process - the mechanisms of formation of granulometric and material composition, the complex transitions that are the rule in nature, and the interactions among different fractions and material constituents. This approach is formalistic and unfortunately very wide-spread.

The other approach, which follows the principles of scientific investigation, is called analytic mapping by the author. Its essence consists in the following: maps of the distribution of individual granulometric fractions are compiled, and then juxtaposed with one another, with the relief of the bottom, with maps of material sedimentary composition, and with the factors that determine sedimentation.

In mapping granulometric composition, the following separate fraction maps are compiled: finer than 0.00 mm, and finer than 0.01 mm (pelitic fractions); then for aleuritic fractions: total (from 0.1 to 0.01 mm) and separately for coarse (from 0.1 to 0.05 mm) and fine aleurites (from 0.05 to 0.01 mm); for sands: total (1-0.1 mm) and separately for coarse (1-0.5 mm), medium (0.5-0.25 mm) and fine (0.25-0.1 mm) sands. If the distribution of gravel-pebble material is significant, data about its content are also plotted on separate map sheets. On the basis of cumulative curves, maps of the median diameter and the sediment sorting coefficient are also compiled, as essential additional information about sediment characteristics.

Practical recommendations for analytic mapping of granulometric composition are given below.

2. The Technique of Granulometric Mapping

For mapping on a given scale, bathymetric or navigational maps are used. In a number of cases, as noted above, it is necessary to do preliminary bathymetrical mapping, and then to place the net of ground stations on that basis.

All the field stations are plotted on the bathymetric map (if data from different expeditions are used, they are plotted with different symbols and colours, as the processing methods may not have been identical). This bathymetrical foundation, showing station locations and their number, serves as the basis for the whole series of specific maps (fractions and components).

It is convenient to draw specific working maps on tracing-paper or on sheets of transparent plastic, so they may be compared easily by superimposing of 2 to 3 sheets, and so that the same bathymetry and station distribution can be used throughout. During the compilation process, maps of separate fractions are constantly co-ordinated with each other, as each map reflects different aspects of a single sedimentation process.

To compile the specific maps, one first plots analytic determination results by station. It is then necessary to delineate, on the maps, areas with fractions contents falling into the following standard intervals: less than 10%, from 10 to 30%, from 30 to 50%, 50-70% and more, and sometimes 70-90% and more than 90% (for the most common pelitic fractions in the pelagic zone).

As the granulometric composition of sediments is closely connected with bottom relief, points with equal contents are expanded into areas not by mechanical or graphic interpolation, but by constant reference to the bottom relief, which is easy, because the relief can be seen through the tracing-paper on the base map (fig. 22).

The mapping procedure is usually begun with identification of rocky outcrops, which are plotted on the entire series of granulometric charts. Results of mapping in regions provided with dense sample nets, and especially direct photographic and TV observations by means of underwater equipment have shown that transitions between granulometric sediment types are usually gradual. Omission of a granulometric sediment type almost never occurs. For example, sands virtually never border muds along a sharp boundary: they usually become gradually finer, turning first into aleurites, and then into muds. The disordered spots of sediments of different granulometric types, which can be seen on old maps, reflect a formalistic, mechanical compilation methodology rather than reality.

Experience shows that granulometric mapping should start with the coarsest fractions, for they are usually concentrated along the shore, and also along the tops of underwater rises, i.e., their distribution tends to be linear or pointwise, with finer material filling in the spaces between.

The density of stations, and hence of data provision in different parts of the map is usually irregular: reliably studied areas alternate with less well studied and even blank ones.

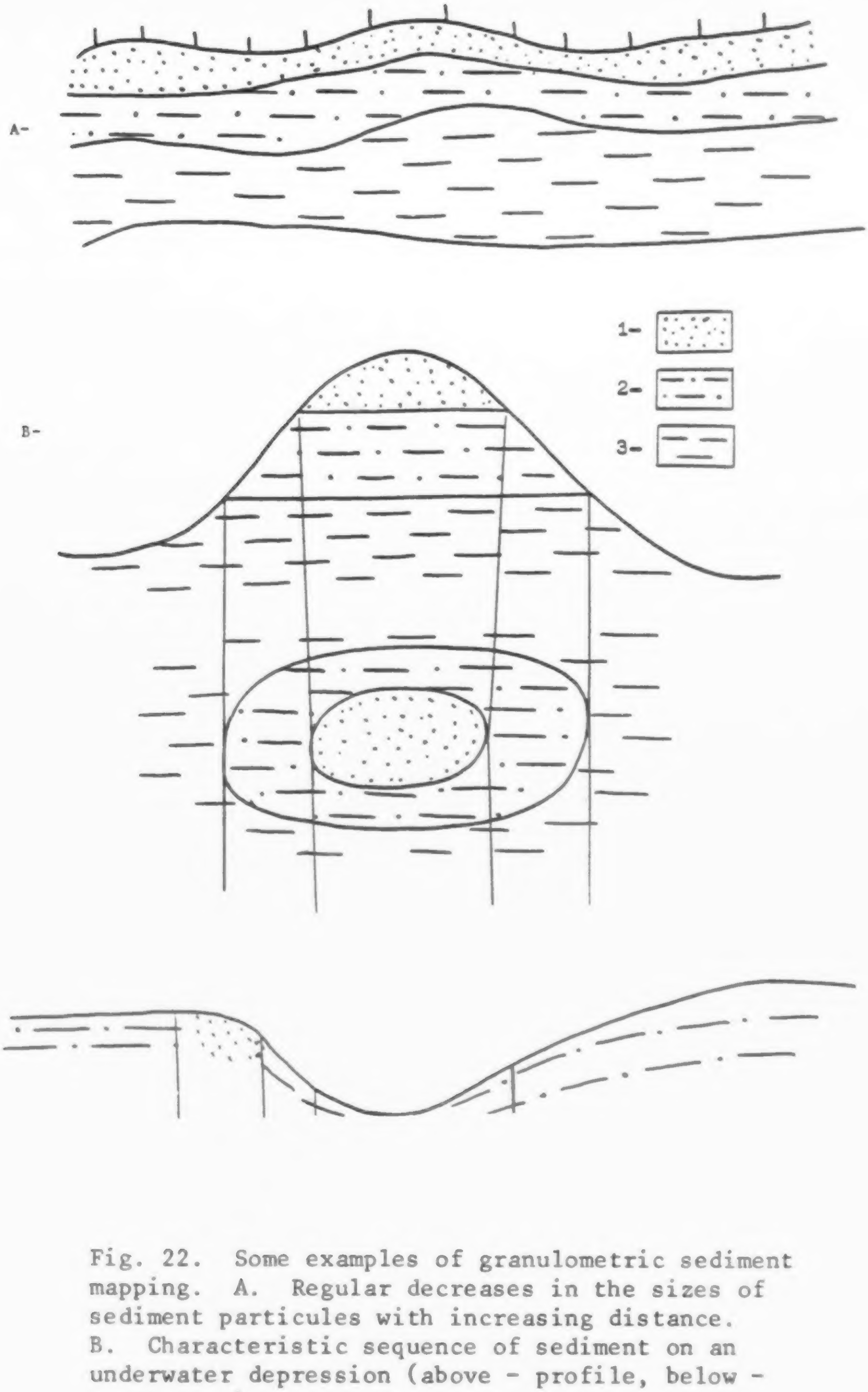


Fig. 22. Some examples of granulometric sediment mapping. A. Regular decreases in the sizes of sediment particules with increasing distance. B. Characteristic sequence of sediment on an underwater depression (above - profile, below - on the map). C. Characteristic sequence of sediments in an underwater depression (above - profile, below - on the map): 1 - sands; 2 - aleurites; 3 - pelites.

Mapping is started from the areas having most stations, with a view to discovering the relationships between quantitative distribution of a given fraction, and bottom relief and other factors. These regularities can usually be extended to areas with fewer stations, and then the distribution can be extrapolated to map sections with no stations, where it is shown by dotted isolines (it is necessary subsequently to check the extrapolation with additional data).

In shallow areas, coarse fractions are the most common and are usually dominated by the sandy fraction. When determining the distribution of this fraction in sediments of a specific region, first a map of total sandy fraction content is compiled (from 1 to 0.1 mm), and then details of the distribution of coarse, medium and fine sands, within the boundaries of sandy fields, are determined.

After the overall sandy fraction distribution map has been finished, the second most important map is compiled - that of pelitic fraction content (finer than 0.01 mm), which fills the spaces among the sandy areas. This map is also compiled in two stages - first for total pelitic fraction and then with finer subdivision.

The third and last map to be compiled shows overall aleuritic fraction content (0.1-0.01 mm).

The principle of distribution of these three main fractions is quite simple - fields of aleurites are usually spreading among fields of sands and pelites. At this stage it is important to co-ordinate each of the maps with the bottom relief (on the base-map) and amongst each other - so that the isolines of fraction contents on the various maps do not intersect, and extend in a consistent manner (the conformity principle).

Sand, aleurite and pelite fields are distinguished according to dominant fraction (more than 50%), to be plotted later on the overall map of granulometric composition. These fields must not overlap or intersect, which is ensured by superimposing and comparing the maps.

The second stage is to detail fraction distribution within sand, aleurite and pelite fields (compiling separate maps for coarse, medium and fine sands, etc.). While these maps are being made, they too are constantly correlated with the relief and with the total content of the given fraction. Ultimately this makes it possible, within the bounds of a fraction field, to distinguish more detailed fields of coarse, medium and fine constituents of the given size fraction (provided the scale of the map allows this). The fields as distinguished are then plotted on the overall granulometric composition map.

The third state involves mapping of median diametres and sorting coefficients, which are obtained from cumulative curves. The working principle is the same: correlation with the bottom relief and with the various fraction maps, thereby revealing many important aspects of sediment formation.

The fourth stage is to determine the relationship between granulometric and material composition of sediments. This is done by the method of "genetic granulometry", which involves studying the fractions obtained during granulometric analysis under a microscope, and also by means of chemical and mineralogical quantitative analysis.

So as the investigations grow more precise, it becomes possible to understand ever finer aspects of the formation of granulometric features of sediments, and the role of granulometry in the formation and genesis of sediment properties. The level of detail of this work is closely connected with the map's scale: the more detailed the sediment map, the greater the necessary detail of study and mapping of the granulometric dimension.

The compiling of each individual mapping sheet is difficult research work, during which the scientists must determine why the given fraction is distributed just so, and not otherwise, and what are the main factors and relations. For the purpose of explaining causal relationships, it is very useful comparatively to study and superimpose the individual fraction distribution maps. Distributions of the various fractions in nature are closely interconnected, and these concrete relationships should be analysed by superimposing (comparing) several maps, and be correctly represented on the overall map.

Microscopical observation of smear-slides and individual bottom sediment fractions, obtained after granulometric analysis, usually makes it possible to show on the map of what material the grains of a given size are composed - foraminifera, shells, diatoms or clastic material. Examination of individual sediment fractions under a microscope is particularly important for large-scale mapping. For smaller scales one can limit oneself to base stations. Examination of granulometric fractions under a microscope, and even more so their analytical study, can clarify how the mixing of sedimentary material of varying size influences the material composition indicators. For example, when the fine sand fraction is dominated by foraminiferal shells, it is evident that increasing this fraction results in greater carbonate content, and so on. In other cases carbonate content is related to coccolithophorids - they are concentrated in the pelitic fraction and the carbonate content rises the greater their presence. Diatomic algae are concentrated in aleuritic fractions.

The overall map of granulometric composition is also used to plot results of visual determinations (from hydrographic charts and from other sources) which often make it possible to correct isoline and boundary positions. Boundaries of aleurite-pelitic muds are determined from the pelitic fraction map (along the 50% isoline), and of pelitic muds - along the 70% isoline. Areas covered by all other granulometric sediment types are distinguished, as noted above, on the basis of predominant content (more than 50%) on the corresponding specific fraction map.

Additional information about the formation of granulometric sediment spectra can be obtained from mapping median diametres (Md), as well as sorting (S_0) and asymmetry coefficients, for example by the methods of factor analysis. Experience unfortunately shows that hitherto attempts to apply complex mathematical models and computers to the study of granulometric composition do not justify the time expended. This does not exclude the possibility of more efficient ways of using computers being developed in the future.

The final stage of the work, which involves discovering connections with the constituents of sedimentary material composition, leads to a significantly deeper understanding of the relationship between particle size and composition in sediment formations of a particular region.

The level of detail of granulometric mapping is determined by the map's scale, as on general maps it is possible to show the distribution only of the major sand, aleurite and pelite fractions. On medium-scale maps, field dimensions are such that subdivisions into fine and coarse sands, and fine and medium aleurites can be indicated. Within pelitic fields, it is often possible to distinguish areas with a pelite content of more than 90%, and also areas where particularly fine pelites (finer than 0.001 mm) predominate.

Finally, when the mapping is more detailed, field dimensions provide an opportunity to use Shepard's triangular diagram (Shepard, 1954, 1973), i.e., to distinguish the fine correlations among the three sediment fractions. Many scientists repeat the same mistake when using Shepard's triangle - they do not compile distribution maps for individual components of the granulometric composition, but just formally plot on one map the granulometric composition as determined, separating areas of similar sedimentary accumulation by border lines. We believe that this approach is incorrect. The distinguishing of areas which are mapped in accordance with the Shepard scheme should be done from individual granulometric maps. For this purpose, three tracing papers are superimposed, corresponding to the triangle's determining fractions: (sands-aleurites-pelites), and then sediment fields of one or another granulometric type are defined.

The main principles of formation of the granulometric sediment types are easily established by such comparisons, as are the relationships with bottom relief and other factors.

It is very useful to supplement maps compiled from triangle Shepard diagrams with separate schemes of median diameters and sorting coefficients, as well as schemes of material composition of the fractions.

More detailed investigations make it possible to apply more precise subdivisions in small triangles of the Shepard scheme. For this purpose, specific maps of the distribution of various sedimentary fractions are again necessary, together with maps of median diameter distribution and sorting coefficients.

There is also an opportunity for detailed mapping of the material composition of different fractions. This composition is determined either by studying the sediment as whole (i.e., without division into fractions) under a microscope, or -more reliably- by microscopic study of separate fractions, acquired in the course of granulometric analysis, and calculation of the content of different constituents in each of these fractions.

For example, when examining fine sandy fractions (0.25-0.1 mm) under a microscope, one calculates the content of benthic and planktonic foraminifera, of coral fragments, fragmental grains, authigenous minerals, etc. The results are expressed in percentages. These types of calculations make it possible to "feel" each fraction, to imagine what changes in sediment composition can result from increasing or decreasing the fraction's content. Composition changes as a function of location, and relationships to various environmental factors and food sources must be studied for each fraction as well.

Such microscopic examination (fine fractions are studied under a scanning microscope) is often usefully supplemented by examination of decarbonated fractions, especially when carbonate dominates in a number of places and makes it difficult to study clastic and authigenous materials. Carbonate material is removed by means of muriatic acid. In a number of cases it is necessary to remove the authigenous minerals as well, as they "block" the fractions (pyrite, glauconite, etc.).

Finally, in some cases microscopic examination is supplemented by the chemical analyses of granulometric fractions, to give the contents of $CaCO_3$, Fe, Mn and other major constituents. For fine fractions it is of great importance to study the mineral composition of samples by quantitative X-ray methods, which have been developed during recent years, and are now being practiced on a wide scale in the deep-sea drilling project (Cook et al. 1975, Gorbunova 1969). By these methods the sample's content of carbonates (separately calcite, aragonite, magnesian carbonates), quartz, feld spars, and a number of other widely distributed minerals is determined quantitatively (or semi-quantitatively).

The principles behind such an approach are evident: it is necessary to determine what constituents (biogenous and clastic minerals, $CaCO_3$, Fe, Mn, etc.) the given fraction bears what happens to the sediment when this fraction's content increases or decreases, etc. Thus, mapping becomes not a formalistic, but a creative scientific process, when the investigator sees, estimates and "feels" each fraction (fig. 23).

From the above, it is clear that the study of granulometric composition is not a geometric or mathematical procedure, since granulometric composition is often influenced by the constituent particles, by their coarseness and vice versa - the sorting processes of particles of a specific size often determine the material composition. In short, the process of sediment formation is binary, in that it is determined by both granulometric and material characteristics of the sediment.

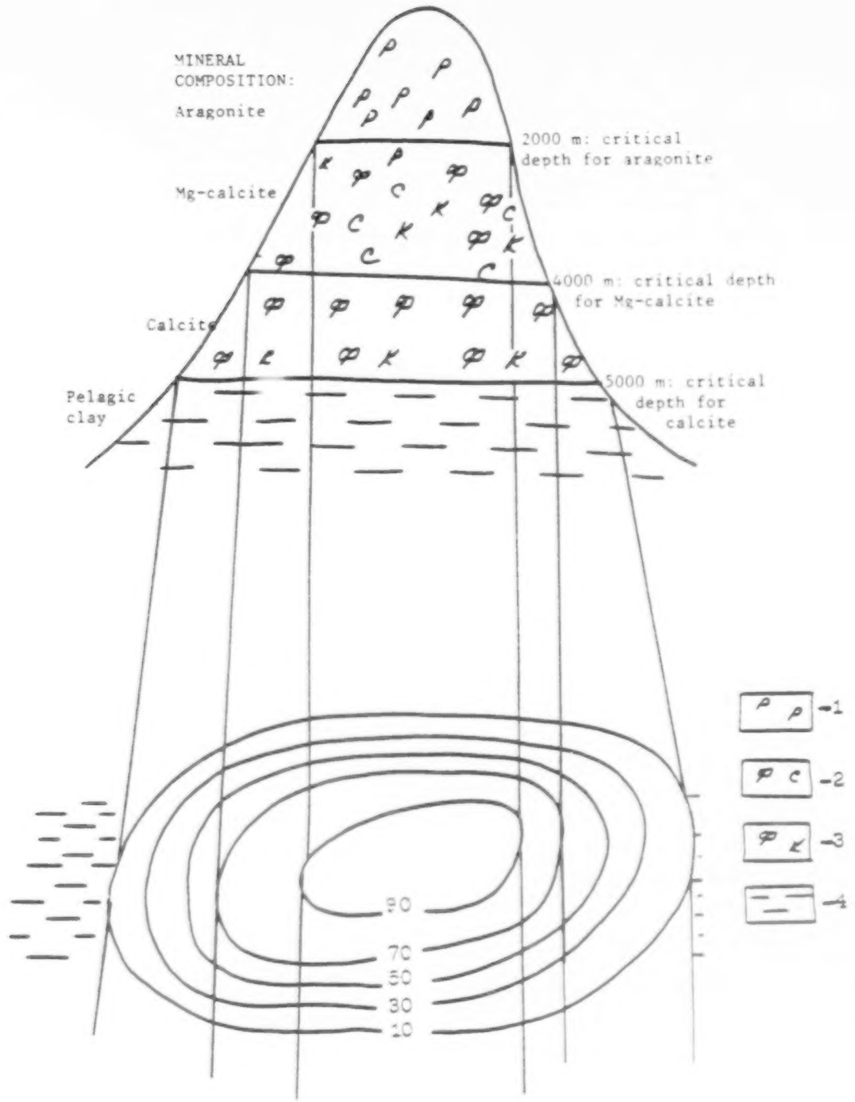

MINERAL COMPOSITION:
Aragonite
Mg-calcite
Calcite
Pelagic clay
2000 m: critical depth for aragonite
4000 m: critical depth for Mg-calcite
5000 m: critical depth for calcite
90
70
50
30
10
-1
-2
-3
-4

Fig. 23. Examples of sedimet material composition mapping. Principles of mapping carbonaceous sediments on an underwater mountain with regard for the critical depths of aragonite, Mg, calcite and low-magnesian calcite. Above - profile, below - on the map.
1 - pteropods (aragonite; 2 - foraminifera and coral fragments (magnesian calcite); 3 - foraminifera and coccoliths. Below the % $CaCO_3$ content is shown by isolines.

By comparing individual fractions, one can see, for example, the disintegration of foraminiferal material from whole shell deposits to fine pelites, composed of separate crystallites. It can be seen how the material of coral and other structures is disintegrated and sorted, how material delivered by rivers is sorted, etc. Such detailed studies make it possible to understand the causal relationships underlying the formation of concrete granulometric spectra and their genesis (in this respect it is of great importance to compare the results with sorting coefficient), and to extend this understanding to large areas of the bottom with changing sedimentation conditions.

Thus the overall granulometric composition map synthesises the results of many-faceted investigations and quantitative granulometric analysis, reflecting all the fine points of this major sediment feature.

3. The Technique of Material Composition Mapping

The main constituents of bottom sediments are $CaCO_3$, amorphous silica, Fe, Mn, C_{org} and P. The role of these components in sedimentation processes and their distribution are not identical. The most common and important along the African coast is $CaCO_3$, for sediments often contain 50-90% of this compound. Other sediment constituents occur much less frequently and abundantly than $CaCO_3$ (figs. 24 and 25).

Siliceous material (diatomaceous and radiolarian) is distributed according to primary production areas: it is most abundant in upwelling zones (the north and south arid zones of the shelf of West and Central Africa), and also in high-production zones of the equatorial divergence of the Atlantic and Indian Oceans. In other latitudinal zones near the shores of Africa, siliceous material is absent (with the exception of some enrichment in rivers near their mouths).

The distribution of organic matter in sediments is also determined by phytoplankton productivity and by depth. Maximum C_{org} contents are registered in coastal upwellings. At small depths (no more than 200 m and rarely at 500-700 m), sapropelic sediments (up to 20% C_{org}) are to be found. At greater depths the organic matter is disintegrated while falling through the water (this is shown by analyses of suspensions from different water levels), and usually does not reach the bottom, i.e., regions of high C_{org} content near the shores of Africa coincide with regions containing siliceous sediments.

The distribution of phosphorus in sediments is closely related to the distribution of amorphous silica and C_{org}, as these three constituents are found in diatom algae shells, which are the main source of primary production in upwelling zones. In arid zones of the Atlantic, phosphorites occur at depths of 150-500 m. In some cases, they are found even deeper along the slope, but then they usually represent ancient redeposited phosphorites, related to stages of ocean level decline. No phosphorites have yet been found on shelves of the western part of the Indian Ocean.

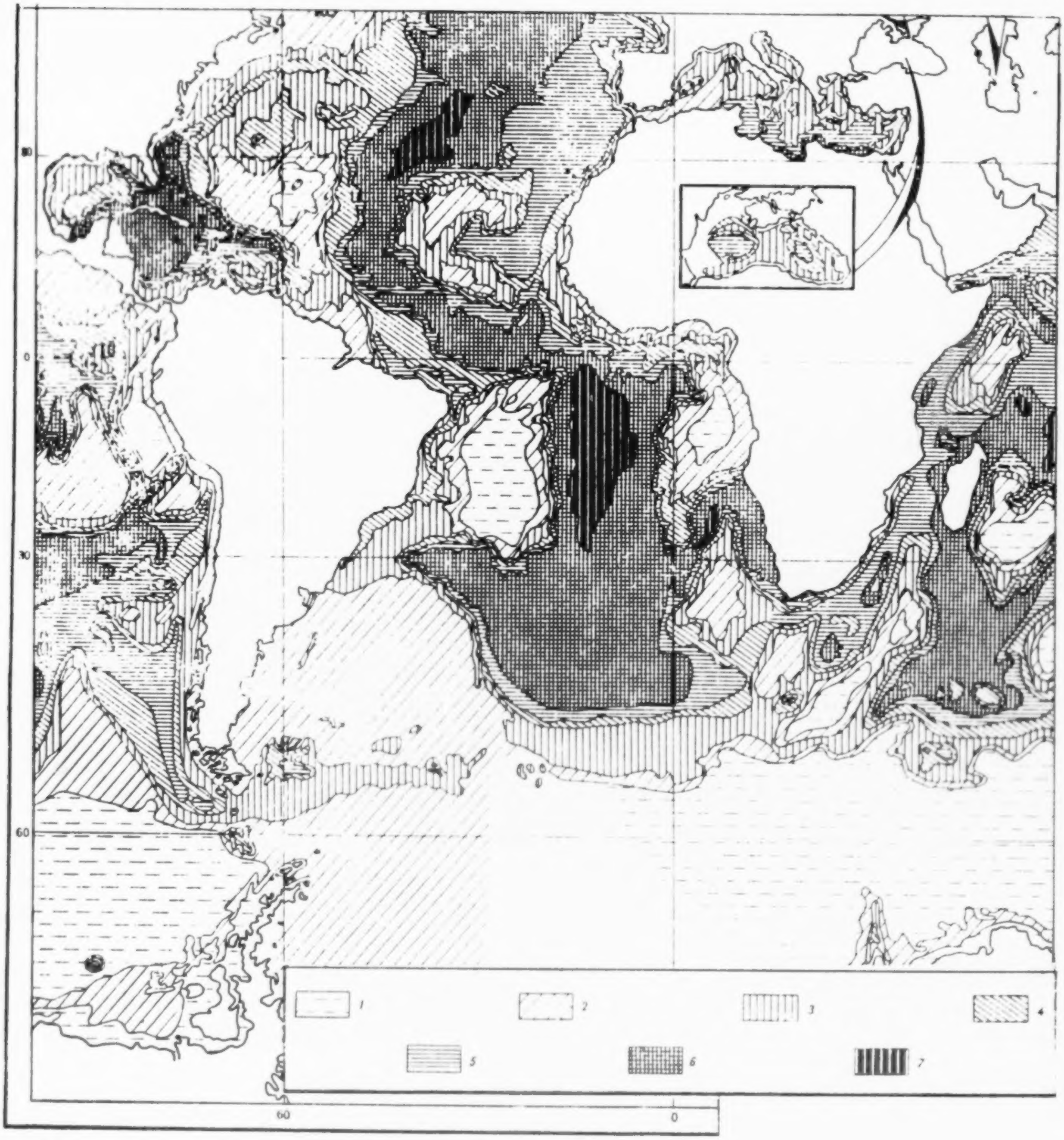


Fig. 24. CaCO$_3$ distribution in bottm sediments of seas and oceans as of natural dry sediments.
1 - less than 1; 2 - from 1 to 10; 3 - from 10 to 30; 4 - from 33 to 50; 5 - from 50 to 70; 6 - from 70 to 90; 7 - more than 90.

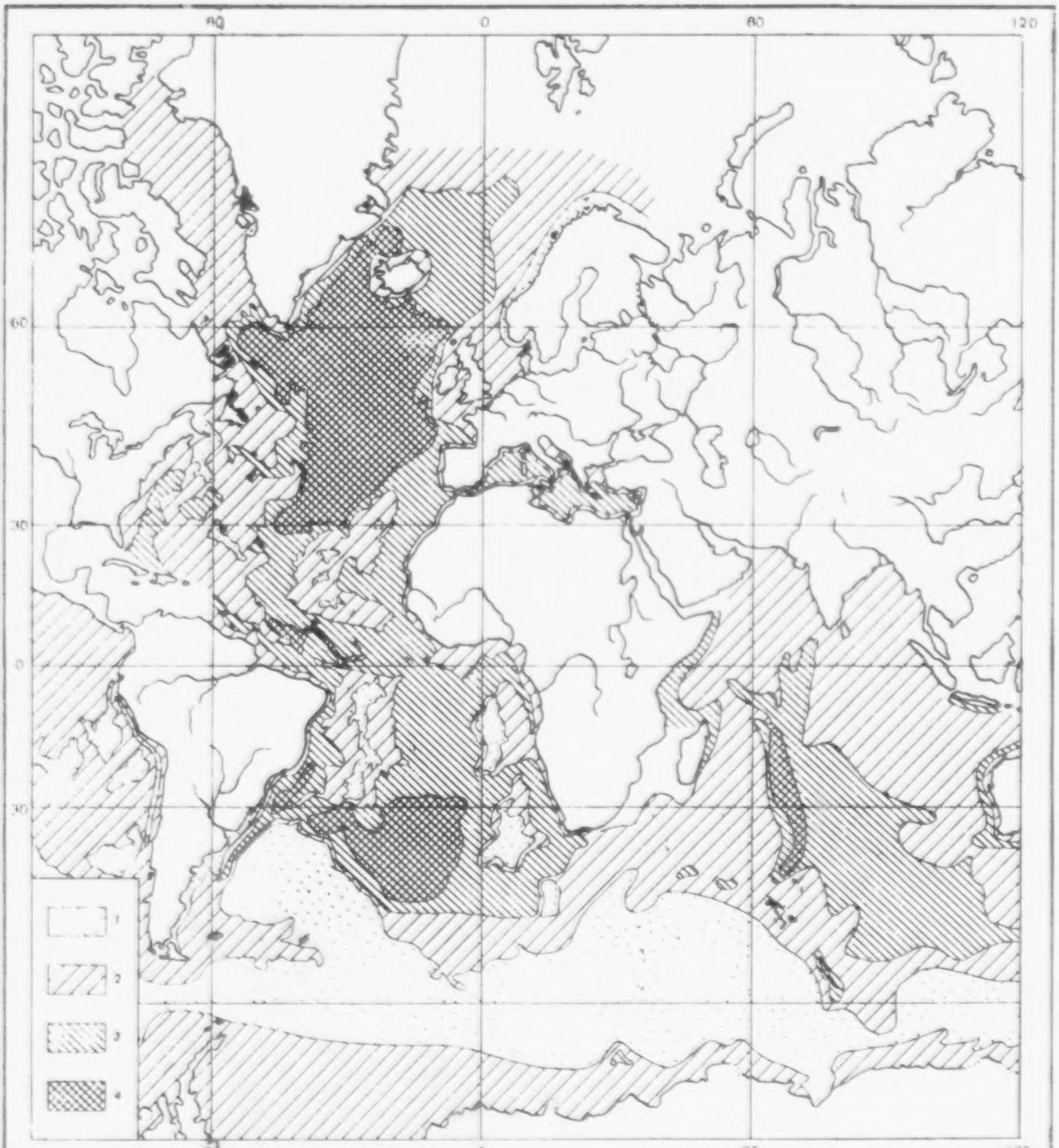


Fig. 25. Quantitative distribution of planktonic foraminifera in the surface layer of bottom sediments of seas and oceans in specimens per g of dry sediment. 1 - foraminifera not detected: 2 - from 1 to 1,000; 3 - from 1,000 to 10,000; 4 - more than 10,000.

Pure phosphate usually comprises only a small part of concretions and nodules, and is represented by fluorinecarbonateapatite. The P_2O_5 content of this mineral is about 32%. Soft pellets of diatomous ooze from the south upwelling contain from 3 to 11% P_2O_5, and solid concretions up to 31-35%. The rest of micro-nodule consists of diatomous shells, foraminifera, grains of quarts and feld spar, and finely-dispersed terrigenous material.

The primary organic matter of diatomous algae, which contains C_{org}, P, N. S and several other elements, disintegrates after the organisms' death, with nitrogen and phosphorus entering the water first followed by C_{org}; the diatomous shells, composed of amorphous opal, penetrate to the greatest depths. Thus, in areas with abundant diatomous algae, a distinct zonation is observed: with increasing depth, sediments rich in N (are replaced by sediments rich in P, and then rich in C_{org}, and finally in amorphous opal). Exceptions apply only to unstable constituents, and hence sediments rich in phophates may also be rich in C_{org} and opal. This must be taken into account while mapping.

Sediments enriched with Fe are found along the shores of West and Central Africa, near river mouths of the equatorial zone (chamosite, glauconite, etc.), and also in upwelling zones (mainly glauconite).

By examining analyses of the above components, one can determine those cases when they attain high concentrations, and exclude the constituents that play a secondary role in the region under study.

Special methods are required for mapping bedrock outcrops on the bottom, which are rather widely distributed. These are often small areas (rocks at small depth). In other cases, on the shelf edge and on steep irregular slopes, there are vast areas of hard rock outcrops.

Within the area of continental crust extension, we find rocks of the continental type: igneous, sedimentary and metamorphic. Near the African shore, outcrops of pre-cambrian, various acid igneous rocks and others are often encountered. In the area of oceanic crust extension, essentially only one type is to be found - oceanic basalts. Their minor content changes are determined by tectonics.

Underwater crops are mapped by the same methods as those used for geological mapping on land, if the rocks are within the limits reachable by divers. The results of chemical and mineralogical analyses are plotted on the map. Beyond the limits for divers, the work becomes considerably more complicated, and often even a large number of attempts to obtain a sample of hard rock from the outcrop on the bottom are successful. The mark "rocks" is indicated on maps when a sediment sample cannot be obtained.

In such places it is useful to apply the tube-chisel. This is a rather short (about 1-1.5 m.) and very heavy tube, with a massive tip of solid steel and an inner mounting of the "orange peel" type made of elastic beryl bronze. The tube is descended at high speed and cuts out rock pieces, which stick in the tip.

Underwater photography and TV appear to be useful, when the surface of rocks can be seen on the ocean floor.

When mapping material composition, it is particularly important to obtain information on primary production of plankton, on benthos biomass and on ecological conditions.

Sediment composition mapping is done by plotting, on separate tracing-paper maps, all the main components of material composition: $CaCO_3$, amorphous silica, C_{org}, Fe (and in some cases Mn as well). As for granulometric composition, the tracing-papers for each component are superimposed on the base-map with bathymetry and station scaterring, then the corners for sheet superposition are marked, and the main lines of coordinate frameworks are drawn. For scattering, all available field and literature data are used and plotted on the tracing paper in different colours. Additional data can also be obtained from visual sediment descriptions, and also from hydrographical maps, which indicate, as a matter of course, the presence of carbonaceous material (shells, corals, foraminiferal sand), nodules, etc.

As in the case of granulometric composition mapping, it is especially important to examine and describe samples under a microscope. When describing $CaCO_3$ or amorphous opal content, it is specified to what particular organisms the opal and carbonate are related, and in which fractions the remains of these organisms are concentrated. Thus, a very important step in mapping work is the study with a microscope, and even better- analysis of the composition of individual fractions of bottom sediments (genetic granulometry). This sort of investigation makes it possible to draw isolines of material composition on the tracing-paper, with regard for the actual distribution of these components by granulometric composition fractions, and to determine the dominant-fraction, whose distribution determines the distribution of the given sediment constituent. The isolines of the given fraction distribution then determine the distribution of isolines of $CaCO_3$ or amorphous silica. The constituents making up the organic matter (P, N, C_{org}, S and others) are related to the pelitic fraction, and therefore the isolines on these maps follow the pelitic fractions (finer than 0.01 mm) isolines.

Iron appears in some cases to be related to pelitic fractions, and in areas with heavy concentrates - to fine-sandy or coarse-aleuritic fractions. In areas containing authigenous minerals (glauconite, chamosite, phosphates, etc), the distribution of components is related to the dimensions of concretions (they are usually associated with sandy fractions). For carbonaceous material, the most common in sediments near the shores of Africa, the areas to be distinguished are associated with coarse material (shells, balanus, corals, etc), with sandy-aleuritic fractions (foraminifera), and with pelitic fractions (coccolithoforids). Thus, after revealing the granulometric dependency of a given sedimentary component, one can with assurance draw its isolines, by comparing actual determinations plotted on tracing-paper with isolines of the determining fraction.

Sometimes there are inconsistencies when the figures from scattering data turn out to be higher or lower than those which follow from the determining fraction's distribution. This happens where, besides this particular fraction, the constituent's content is influenced by other fractions, which can usually be established from microscopic and macroscopic descriptions. Such descriptions must always be available while maps are compiled. Usually the isolines run parallel to the isolines of the given component's determining fractions.

Isoline intervals are chosen in accordance with the gradations of the classification scheme. Given a sufficient density of sample points, it is possible to draw a number of intermediate isolines, which help in understanding the details of the component's distribution in relation to the environmental conditions.

The mapping begins with the most common constituent of sediments, i.e., $CaCO_3$. Sections where $CaCO_3$ has high significance for sedimentation processes are shaded in accordance with isoline gradations - they will later appear on maps of bottom sediment types. Different shadings are used to distinguish areas containing 10-30%, 30-50%, 50-70%, 70-90% and more than 90% $CaCO_3$.

Then the distribution of amorphous opal is mapped; this constituent is connected with aleuritic and pelitic (shell spine fragments of diatoms) fractions of the granulometric composition. Areas containing 10-30%, 30-50% and more than 50% opal are distinguished and shaded on the maps.

On the Fe content map the following areas are distinguished by shading - from 5 to 10%, from 10 to 20% and 20 to 30%. Sections with sediments containing more than 30% Fe occur rather seldom.

On the Mn maps areas with 0.2-5% and 5-10% are highlighted by shading.

In accordance with the classification, areas of different sediment enrichment by C_{org} are also distinguished.

Appart from the shading, in order to enhance genetic understanding of material composition, marks are put to indicate the main and secondary sedimentation organisms (foraminifera, shells, coccolithoforids, pteropodes, corals, diatoms or radiolarians, etc.), or the processes by which concentration of a given component is determined (authigenous glauconite, phosphates, ferrum-manganese nodules, etc).

When drawing isolines on tracing-paper, as noted above, one should be guided by tracing-papers of granulometric composition, and one should compare the tracing-papers of material composition among each other and with the relief map.

Generally speaking, the isolines must not intersect bottom relief isolines, or the isolines of granulometric and material composition. This rule of course has many exceptions, which must be carefully examined and justified case by case.

The final stage of material composition mapping is to compile the overall tracing-paper. The areas where the components' contents have sediment-forming significance (shaded zones), are transferred to it from the individual maps of material composition. These zones are coloured on the overall tracing-paper in accordance with the final map's legend: $CaCO_3$ - different shades of blue and dark-blue, amorphous silica - green shades, iron - rust-brown tones, manganese - violet, C_{org} - grey.

When a sediment is enriched with several components (for example, upwelling sediments containing amorphous silica, phosphorous, and sometimes iron in glauconite form), the material composition of the sediment is shown by stripes of corresponding colours. The colour intensity within stripes must often be changed, when the content of the given component varies. Such complicated areas can be mapped quite easily, by superimposing the individual sheets of tracing-paper, and then transferring their markings to the general sheet. This last material composition sheet gives the colouring of the final sediment map.

The last step is to combine granulometric composition data (as plotted by shading on the overall granulometric tracing-paper) with the overall material composition map. If, as recommended above, during the compiling of individual tracing-papers of material composition, they were constantly superimposed on the maps of particular fractions and other components, then usually there are no contradictions among the maps. Isoline paths highlight the logic of the sedimentation process, and constant consideration of the bottom relief reveals fine changes in the process at underwater rises and in basins.

All bedrock outcrops on th bottom are plotted on the final material composition map, by means of conventional signs from geological map legends. For sedimentary rocks, age must be shown in addition to material composition.

4. The Compiling of General Bottom Sediment Maps With Different Scales

The compiling of bottom sediment maps is fascinating research work, which requires a creative approach. It is very important that the map be as objective as possible not only in showing the distribution of the sediments of different granulometry and composition, but also in cartographically representing the specific nature of the sedimentation process in the given region.

In compiling their maps, scientists begin with the areas best covered by hard data, and then extend the work further to less studied areas, using the relations they have discovered making well-founded regional lithological extrapolations for poorly investigated areas. Such relations are established gradually, not only for individual sheets of tracing-paper, but also for the entire material composition group, as well as the granulometric composition tracing-papers. The scientist begins to "feel the sediment", predicting what will happen as depths or distances from the shore change, or under the influence of other factors. This makes it possible to draw isolines with greater assurance. There always remain places, which are insufficiently studied for one reason or another, and these isolines are drawn as dotted lines. Separate map sheets, of the same scale and covering a substantial bottom area, are attached along the margins, in order that isolines continue from one sheet to another as they are compiled.

It is advisable to compile a geomorphological map and a map of the bottom surface microrelief, in addition to the set of bottom sediment maps (sediment types and major components). In addition to morphostructure and mormphosculpture, the geomorphological map must show elements of modern tectonics, in particular rates of current vertical motion and details of plate kinematics (direction vectors and rates of plate motion). Naturally, these maps are compiled on the general map scales.

Choice of the mapping scale

According to the scale, we distinguish among general maps with the scale 1:2.5 mln and more, regional maps from 1:2.5 mln to 1:500 thousand, and local - with scales from 1:50 thousand to 1:25 thousand, and sometimes even 1:10 thousand.

The mapping scale is determined to a large extent by the purpose of the investigation and the depth of the region. At present we have examples of geological mapping of deep-water ocean bottoms on a scale of 1:25 thousand and even more detailed than that. In such cases, one starts with a bathymetrical and geophysical survey of the polygon, and then one does the geological mapping. Based on a fixed station network, samples of bottom sediments are selected. The final stage of investigation involves using manned research submersibles on the bottom to carry out a geological route survey and to collect samples along the given routes.

The limiting factor determining mapping scale is the precision of navigational referencing of tacks and of individual instruments at the stations.

When planning echo-sounding and sample collection by the system of parallel tacks, the basic principle is that the distance between sounding lines on the map must not exceed 10 mm, i.e., if the mapping is on a 1:10,000 scale, the distance between tacks must amount to 100 m., while if the mapping is at 1:100,000 this distance should be 1000 m.

For small-scale mapping, it is usual to use a network consisting of a system of profiles, along which the sediment sample collection points are located. The distance between profiles and points, as in the case of sounding, depends on the mapping scale. For a scale of 1:100,000, the distance between profiles is taken as 1 km, for a scale of 1:200,000 - 2 km, and for 1:500,000 - 5 km.

There exists a close relationship between the distance separating profiles and sample collection points on the profiles, and the ship's position determination error: the more detailed the survey, the greater the ship's position accuracy requirement. It is usually considered, that the distance between profiles and sample collection points on the survey framework must be no less than 2-3 times the ship's position determination error.

The survey framework can be arbitrarily oriented with respect to the cardinal points, but measures must be taken to ensure that tacks are located across boundaries of sediment type and other changes.

When working on a shelf, the survey framework is usually oriented so as to run the tacks perpendicular to the coastal line.

This principle for choosing the survey scale, as a function of the determination error, is intended for even bottom sections, where changes in sediment types are very gradual and mostly regular. Things become much more complicated when the relief is sharply disjointed - on the brow of the continental slope, in areas with valleys and canyons, and especially when the continental slope is steep. Then, the station network must be made as dense as possible, since sudden changes in the bottom relief cause sudden changes in the distribution and composition of sediments, and widespread occurrence of ancient rock outcrops. For such particularly complex and disjointed sections, it becomes necessary to delineate sections covered by sediments, as often considerable expanses of the slope have no sedimentary cover, and the bottom displays outcrops of bedrock or ancient consolidated sediments.

5. Lithologic-Radiometric Mapping

Sediment mapping on the shelf can be improved significantly by using one of the simplest geophysical instruments, namely a marine gamma-spectrometer.

The principles of marine gamma-spectrometrical surveying, as developed at the Institute of Oceanology, Academy of Sciences, USSR, (Kostaglodov, 1979), are based on the fact that different types of bottom sediments, as well as rocks exposed on the bottom, have different contents of natural radioactive elements.

Modern instruments make it possible not only to determine the total gamma activity, but also to separate it by energy spectrum into at least three parts: uranium (1.65-1.95 MeV), potassium (1.0-1.6 MeV) and thorium (2.3-3.3 MeV). The sulphidic activity is also determined. The average contents of these radioactive elements in shelf sediments are shown in Table 8 and on figure 26.

In addition, it should be mentioned that the uranium contents of phosphoritic nodules and grains are exceptionally high, which makes gamma-surveying a very reliable method for mapping phosphates. Uranium is partly concentrated in heavy minerals (monazite, zircon), while in fine-grained sediments its major part is sorted by organic matter from ocean water solutions and accumulates in the sediments. The uranium-to-C_{org} relation is so close in sediments, that it can be used on a regional scale for rapid mapping of C_{org} distribution. With a

Table 8

Mean content of main radioactive elements and total γ -activity for main types of bottom sediments of shelf zone

Types of sediments	U (Ra), 10^{-4}%	Th 10^{-4}%	K, %	Total γ -activity, u 10^{-y}%	Th/u
1. Bottom Sediments					
Sand					
carbonaceous	0,3	0,5	0,09	0,56	1,6
quartz	0,41	1,52	0,64	1,52	3,7
Quartz with some aleurite (10%)	0,66	2,25	0,8	2,15	3,4
with aleurite (up to 30%)	1,1	3,42	1,16	3,41	3,1
enriched with heavy minerals	6,11	35,0	0,65	18,9	5,7
Ooze					
clayey	1,4	8,2	2,8	6,87	5,8
with some Fe-Mn nodules)	16,8	8,5	2,5	17,7	0,5
2. Sedimentary Rocks					
Limestone	1,4	0,5	0,2	-	0,4
Sandstone	2,0	5,0	1,1	-	2,5
Agillitic schists	3,0	10,0	2,4	-	3,3
Ancient clay	4,3	13,0	2,7	-	3,0
3. Minerals					
Quartz	1,7	0,45	-	-	0,26
Monazite	300-2200	300-50000	-	-	-
Zircom	350-1350	1000-15000	-	-	-
Sphen	2800	510	-	-	0,18
Epidot	430	210	-	-	0,50
Apatite	70	70	-	-	1,0

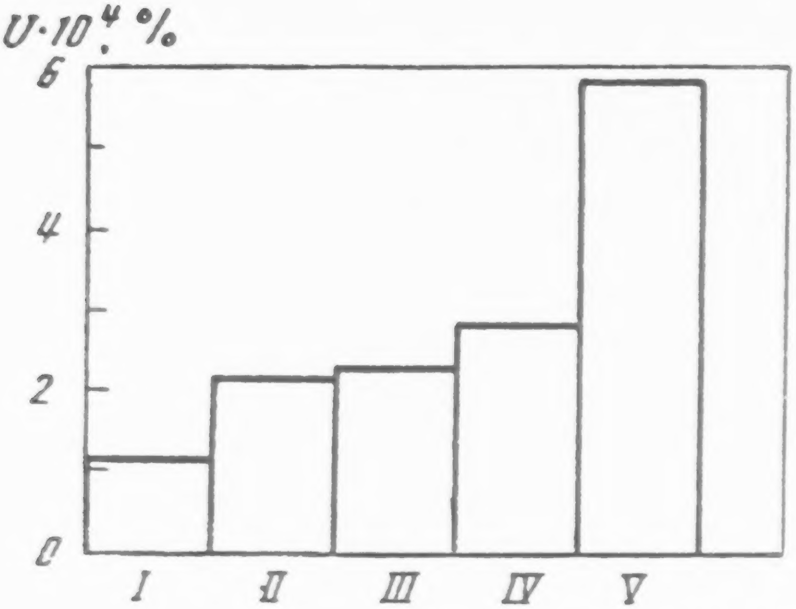


Fig. 26. Average uranium contents for the main types of terrigenous shelf zone bottom sediments. I - sands; II - aleurites; III - fine-aleuritic muds; IV - aleuritic-pelitic muds; V - terrigenous low-calcareous pelitic muds (abyssal).

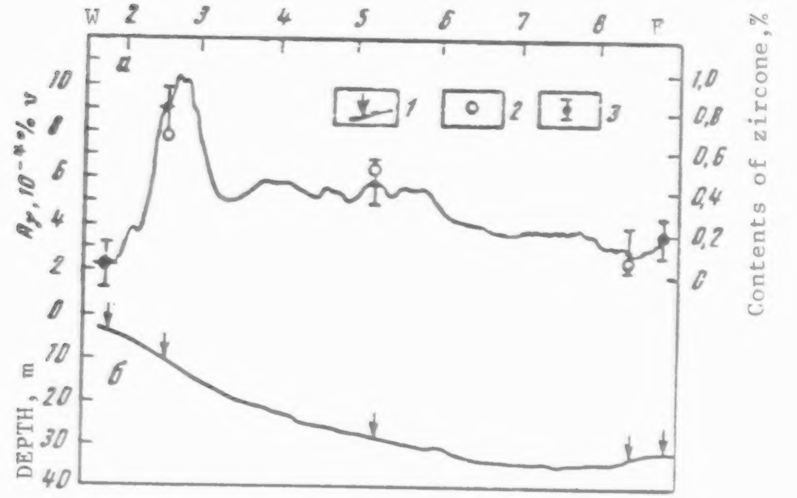


Fig. 27. Distribution of zircon content by profile calculated from radiometrical survey data in the eastern part of the Baltic Sea (a), and depths from echosounder records (b). 1 - points of collection of control sediment samples; 2 - zircon content in samples from results of mineralogical analyses; 3 - Calculated zircon contents at samples collection points.

sufficient number of control sediment samples the method becomes quite reliable. In shelf sediments, depending on regional characteristics, uranium content varies by a factor of 600 or more; in many places, uranium is correlated not only with organic matter and phosphorus, but also with Fe and Mn, due to its sorption by oxide-hydrates of these metals (Baturin 1975 et al.).

Potassium content in bottom sediments varies by a factor of 10-15, ranging from 0.3 to 3.5%. Potassium is associated with feld spar and micas, and in muds with clayey minerals. In glauconite, K content reaches 8% and thus the "potassium channel" can be used for mapping glauconite sediments. K content in sediments falls rapidly as $CaCO_3$ content rises, which can be used for local mapping of $CaCO_3$, with constant control and calibration of course.

Most of thorium is related to heavy minerals, especially to zircon and monazite placers - this is one of the most promising ways of searching for and mapping such placers (figs. 27-28), which are highly probable on the shelf of Africa. In pelagic sediments the content of this element falls to background abundance, but in red abyssal clays and especially in ferromanganese nodules, it again increases by a factor in the hundreds. This maximum is also detected in hydrothermal sediments near mid-oceanic ridges, and is related to that part of thorium which is dissolved in water with hydroxides of Fe and Mn (Lisitzin et al., 1980).

Thus, the geochemical properties, and consequently, the places of uranium, thorium and potassium concentration differ radically, so one can use the peculiarities of their distribution for sediment mapping. It is important to know not only concrete data about the content of these elements in sediments, but also the correlations among them (moduli), in particular, thorium/uranium, thorium/potassium, uranium/potassium and others. For instance, knowing the thorium/uranium modulus it is quite easy to distinguish monazite (modules of 25 to 40) from zircon (modules of 0.2 to 0.5).

On the basis of gamma-spectrometry of primary samples, obtained in a particular investigation region, one can determine content values for these elements along corresponding channels, as well as their relations with bottom sediment properties.

The intensity of sediment radiation depends on the sediment's solid phase content; the lower this intensity, the more water there is in the sediment, i.e., the higher the humidity. This is therefore a method of mapping humidity, which is known to be closely related to granulometric composition.

Marine gamma-spectrometric surveying does not differ much from that used on land.

The equipment comprises a gamma-probe, which is usually trailed along the bottom as the ship follows tacks at 3-5 knots, a towing cable, and measuring and recording devices located on board (Kostoglodov, 1979).

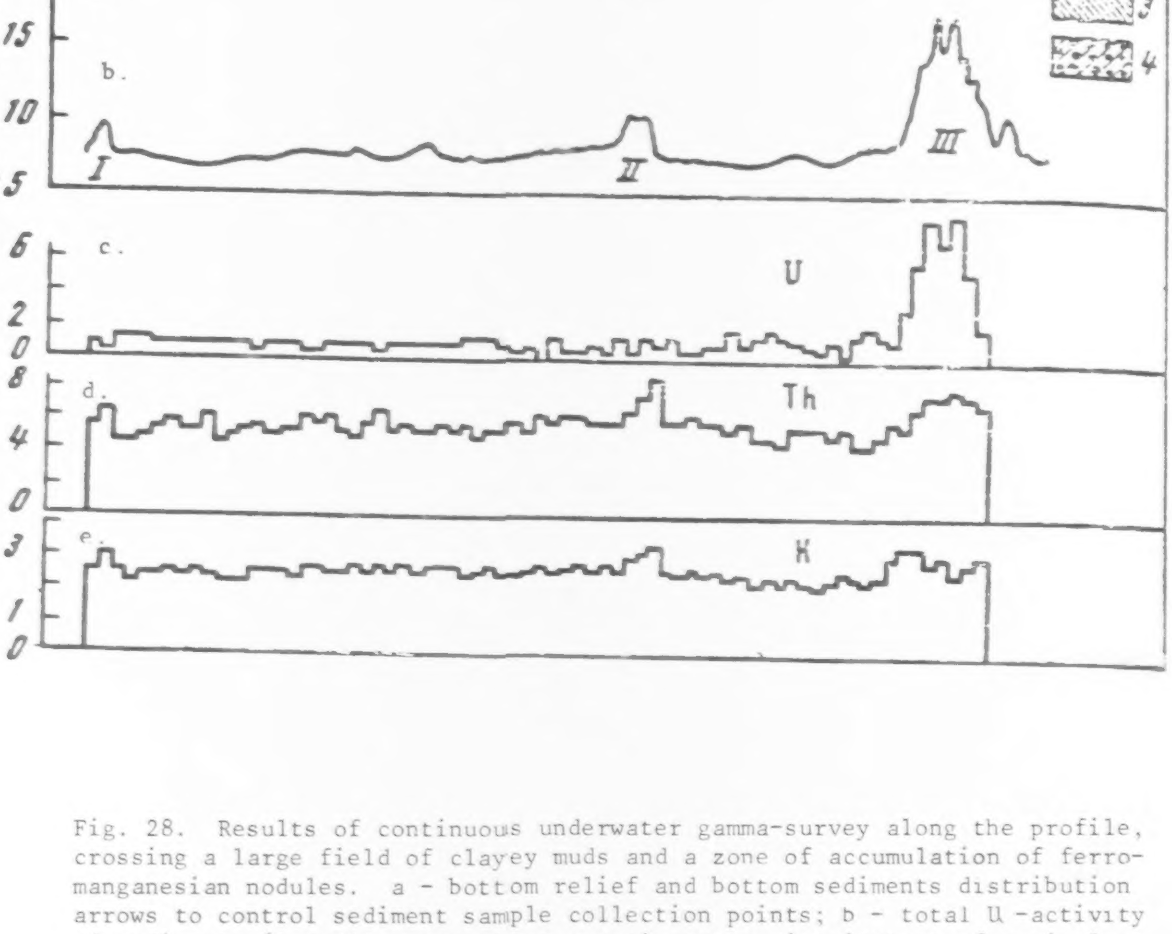


Fig. 28. Results of continuous underwater gamma-survey along the profile, crossing a large field of clayey muds and a zone of accumulation of ferromanganesian nodules. a - bottom relief and bottom sediments distribution arrows to control sediment sample collection points; b - total U -activity of sediments (I - III - anomalous areas); c-e - distribution of equivalent contents of U (Ra), Th, K.
Conventional designations: 1 - poorly sorthed, mainly sandy sediments; 2 - zone of accumulation of ferromanganesian nodules; 3 - clayey muds; 4 - original late-glaciation sediments.

The surveying is generally done with ships that displace more than 50 tons, but in some cases smaller ships and even amphibian vehicles may be used.

Apart from the most sophisticated equipment 4-channel definition (total activity, potassium, thorium and uranium channels), simpler gamma-radiometric devices without spectrum separation are widely used as well. Spectral data are acquired from a network of stations, where samples are collected and examined with conventional gamma-radiometric devices. But experience shows that it is preferable to use more sophisticated 4-channel devices with automatic recorders and computer processing.

It has already been noted, that apart from sediment mapping, the gamma-method can be used for searching for placers of monazite, zircon and other heavy minerals, and for mapping phosphorites, glauconite and shallow-water ferromanganese nodules. This method also proves to be effective for mapping ancient igneous rock and sedimentary rock outcrops, for revealing sections of tectonic disturbance on the bottom, for lithodynamic studies, invesrigation of the geochemistry of radioactive shelf elements, and for detecting radioactive pollution of bottom sediments.

Gamma-survey methods provide information on radioactive mineral contents only in the upper (0-30 cm) sediment layer. In order to study their vertical distribution (for example, in placers), it is necessary to supplement the lithologic-radiometric survey of the surface layer with radiometric studies of cores.

A great advantage of this investigative method is the continuity of recording it with high productivity and the possibility of mapping many parameters, which cannot be obtained by conventional methods. It is also important that this method allows for automatic processing by computer, and establishment of a data bank.

The examination of abyssal sediment by lithologic-radiometric mapping methods has hitherto been done mainly by bottom scoops and tubes, with the use of on-board devices, and is of great help in mapping.

It can already be said, that lithologic-radiometric surveying is an important addition to the study of sediments by traditional methods, that it widens the scope of sediment mapping, and is very important for prospecting for useful minerals on the shelf.

6. Magnetic-Mineralogical Mapping ($\varkappa$ Survey)

For the mapping purposes yet another geophysical method can be used, based on distinguishing among sediments by their content of magnetic minerals. It involves measuring magnetic receptivity ($\varkappa$) in sediments, and can therefore be called kappometry.

Magnetic receptivity measurements in abyssal sediments show, that the $\varkappa$-values vary by a factor of 20-40, depending on the magnetic mineral content (from 3×10^{-6} to 100×10^{-6} CGSM, Linkova, 1982), (fig. 29).

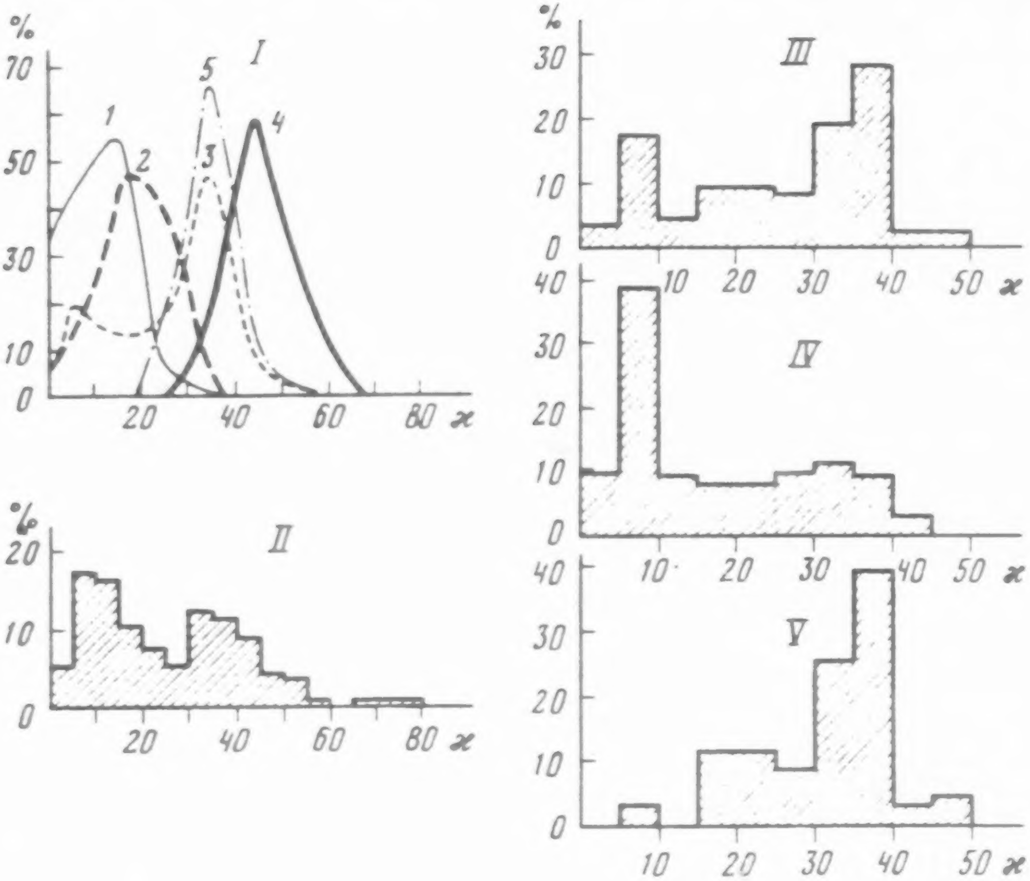


Fig. 29. Distribution of magnetic susceptibility of different types of sediments. I - distribution curves for: 1 - foraminifera and coccolithic-foraminiferal oozes, 2 - coccolithic and foraminiferal-coccolithic oozes; 3 - siliceous sedimeents; 4 - eupelagic clays; 5 - miopelagic muds; II - foraminiferal and coccolithic oozes, P = 647; III - siliceous sediments, p = 113; IV - muds, P = 46; V - diatomic-radiolarian oozes, p = 67.

Measurements are taken by means of a very simple and inexpensive standard kappometer. Kappometric measurements can be discrete, taken in sediment samples lifted on-board, or continuous, like gamma-mapping. Continuous sediment study by the $\varkappa$-method is seldom used, but it can prove to be very useful in areas containing ferro-magnetic minerals, and in particular for placer mapping. It is not very difficult to install a kappometer together with a gamma-detector on towed "sledges" made of non-magnetic materials. The ferro-magnetic fraction of bottom sediments generally consists of magnetite, titanomagnetite, Fe-hydroxides, pyrrhotite, hematite and other minerals.

The mapping of distribution areas of such minerals on the shelf is only one of the tasks of kappometric surveying (Brusilovsky and Glazovsky, 1973; Argikov et al., 1975; Kochemasov, 1979). A second is the determination of admixtures of pyroclastic material in bottom sediments, for pyroclastics usually contain many magnetic minerals. The receptivity of tephra may reach 70 x 10^{-6} CGSM. A third is the detection of outcrops of igneous and sedimentary rocks with high magnetic receptivity, on the bottom surface or under a small layer of bottom sediments. For basalts and granite the values of amount to 100-200 x 10^{-6} CGSM.

Finally, another way of using this method is to study underwater hydrotherms and sulphide accumulations. Pyrrhotite plays a major role among sulphides, and scattering aureoles around hydrotherms are enriched with Fe hydroxides. Hence kappometry can be used to search for hydrotherm outcrops and associated sulphide ores on the bottom.

This rapid geophysical method of describing cores makes it posible to determine areas containing scattered pyroclastic material or Fe hydroxides, and other minerals of the ferromagnetic fraction as well. In addition, since magnetic receptivity, like gamma-activity, is related to sediment humidity, humidity changes which generally correspond to changes in the sedimentation rate, can be traced in homogenous sediments.

Of course, there exists more precise methods for studying ferromagnetic minerals, but they are not used for mapping.

7. Investigations with Side-Scanning Sonars and Continuous Seismic Profiling

When one works with the usual (wide-angled) echo-sounder, many features of bottom relief are not recorded, as the echo-sounder is recording distances to the nearest points on the sea-bottom. Narrow-beam echo-sounders are used only on research vessels, which is also true of multi-beam devices. The latter have from 15 to 72 beams, directed at different angles to the horizon, so that not only the bottom immediately under the ship is examined, but also a wide strip to the ship's sides.

Many bottom relief features, including bedrocks outcrops, especially on the continental slope, are very clearly visible on echograms when a side-scanning sonar (SSS) is used. We obtain the same effect from the SSS as when photographic land relief from an aircraft with the sun near the horizon, when even objects of small height cast long shadows, unevennesses are stressed and highlighted on recordings (fig. 30).

There are systems for towing behind the ship near the surface, and there are deeply towed systems, where the influence of surface layer noise is reduced. Both boomers and sparkers are used as sound wave sources for SSS. Modern SSS systems are portable and can be set up even on small cutters and motor boats. Given some practice with scanner records, one can distinguish rocky exposures and coral structures, gravels, pebbles, sandy waves and reefs, and also canyons and underwater valleys, the areas of landslides and slips, and others. There are also automatic methods for distinguishing among different types of sediments on computer (Rent et al., 1985).

When studying loose sediments, it is very important to do a preliminary survey by the method of continuous seismic profiling (CSP). This is a way of studying the sedimentary thickness to dozens of metres, and when low-frequency systems are used - to many kilometres. The resolution, i.e., the minimal sediment layer that is revealed on CSP records at low frequencies (5-200 Hz), amounts to 30-50 m., and at high frequencies (3-5 KHz) it comprises the first few metres.

During preliminary work on medium and large research ships, echo-sounding and CSP are conducted simultaneouly, since they operate on different frequencies. This makes it possible to see not only the bottom surface, but also separate marking layers imbedded in loose sedimentary deposits, to see details of the internal structure of loose layers, to trace areas with wedged layers and outcrops of relatively dense and ancient sediments or bedrocks, areas covered with saline or clayey diapir folds, tectonic disjunctions reflected in the layer structure, and especially clearly - slide and slip blocks, and areas with turbidites near the base of the continental slope. If it is necessary to examine the entire thickness of the loose layer, then low-frequency systems are used in addition to high-frequency profiling (3-5 Hz).

The methods of seismostratigraphy allow us to correlate individual layers, on regional and global scales, by the use of sedimentation intervals on the shelf, which are related to global ocean level drops and removal of sedimentary material from the first global level of avalanche sedimentation to the second (Vail a.o., 1977, Lisitzin, 1984).

Studies of loose sedimentary structure are developing very quickly, mainly because of oil and gas prospecting on the shelf. These methods can be used to search for other useful minerals, in particular, phosphoritic interlayers in loose sediments, constructing materials hidden in the sediment layers of placers, etc.

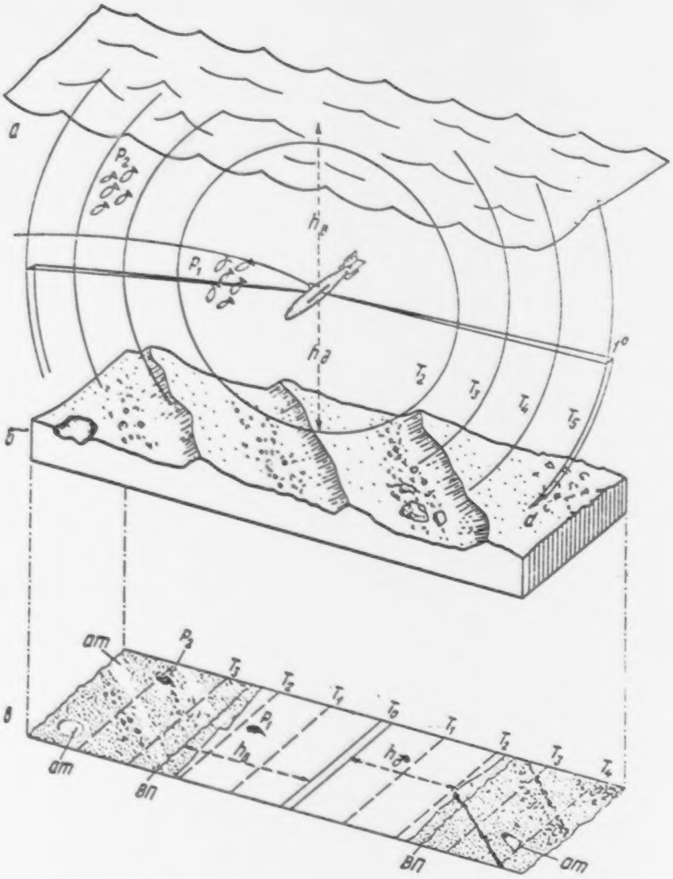

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Fig. 30. Working principle of the side vision sonar for bottom sediment mapping. a - water surface, b - bottom with riple signs, depressions filled with rock fragments and local depression to the left; c - acoustic recording (sonogram), T_o - line of motion of the acoustic source ("fish"), T_1, T_2, etc. - distances to the reflecting object, am - acoustic shade, P - fish shoal and its acoustic reflection; d - resolution-capacity - distance from the source to the bottom.

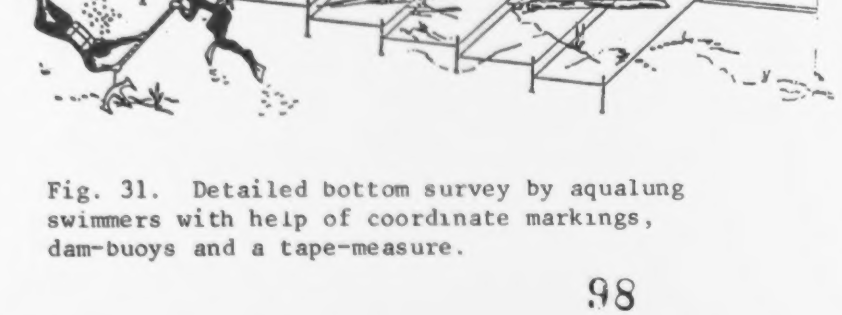

Fig. 31. Detailed bottom survey by aqualung swimmers with help of coordinate markings, dam-buoys and a tape-measure.

8. Additional Investigations by Means of Underwater Photography and Television

In many cases it is necessary to conduct a visual examination of the bottom, in order to scrutinize details of bedrock outcrop locations, special features of the bottom surface, etc. At small depths and especially in the coastal zone such observations are made by divers, but at depths greater than 500 m. they are replaced by photographic cameras and television units.

Underwater cameras can take single photographs (often as samples are collected by bottom-scoopers), or series of several dozens or even hundred photographs, situated along specific tacks. In such cases "anti-drifting" sounding is very useful, as it allows for "sight photography" of the main bottom relief features and key sections. With the tack system it is possible to cover fairly large bottom areas with discrete photographs (Atlas of underwater photographs of the Red Sea rift zone, 1983). Accurate referencing of photographs, and their subsequent location on a special tracing-paper with station numbers are absolutely necessary. This tracing-paper is superimposed on the maps of granulometric and material compositions, and also on the bottom relief map. It can be used as a basis for compiling a map of the bottom micro-relief, which usually varies over different sediment types. Photographs are also very useful for compiling lithological-facies maps.

The most sophisticated underwater devices usually comprise an unmanned underwater vehicle (towed or independent) with a black-and-white or colour camera (often a stereocamera). The reserve of film and power for a xenon flash (strobe) makes it possible to take up to 10 thousand photographs of the ocean floor during one submersion. When the apparatus is towed along a system of tacks, something like an air photography survey can be obtained, with overlapping between shots and between tacks. After enlargement the photographs are arranged according to tacks, or superimposed photomontage is done, which is more difficult.

Modern TV cameras are portable enough to be installed on towed crafts. The picture is fixed on a video tape recorder. The most essential features of the bottom surface can then be photographed from the screen. The tacks of the TV reconnaissance are also plotted on a separate tracing-paper, and then used as supplementary material for bottom sediment mapping.

9. Additional Investigations with the Help of Divers and Manned Vehicles

Visual examination of the bottom with the possibility of rational sample collection according to a fixed system of cross-sections or a network, make geological surveying of the bottom similar to geological mapping on land. A great advantage is that the level of investigation detail can be changed quickly when the relief and sediment distribution situation becomes more complicated.

Complex diving investigations have now become quite common in connection with the building and operation of oil platforms on the shelf. The diving team usually stays in a chamber on board the ship, under pressure corresponding to the working depth, and is delivered to the required ocean depth in a closed bell or by an underwater diving chamber.

Underwater diving is most commonly used for coastal studies at depths down to 50 m. Divers in ligth suits work along specific routes, using compasses, underwater aliuads and tape-measures (Miln, 1984), (fig. 31). Often underwater polygons are set up, with installation of long-term operating devices, for example, sedimentary material traps.

When taking samples, divers orient themselves by an orientation system set up on the bottom, or come to the surface, where they are located by theodolites from the shore.

For examination of more sizeable bottom areas, underwater towed crafts of various types are used.

Small underwater vehicles (minisubs) began to be used widely in the sixties. Underwater research vehicles of various designs can work down to the greatest depths of the ocean. The greater the depth, the more expensive and complex to maintain the underwater vehicles. From the mid-seventies, underwater submersibles with a divers' compartment have been used, which has greatly improved diver mobility and safety during work on the bottom.

It is evident from what has been stated above about bottom sediment mapping at different depths, that the greater the depth, the relief irregularity and the distance from land, the more complex and expensive the mapping operation. As mapping becomes more detailed, requirements regarding navigational referencing of measuring tacks and sample collection points also rise, and in most cases it is precisely the issue of co-ordination that limits the level of mapping detail. That is why the most detailed maps of bottom sediments are presently compiled for shelves, in connection with placer exploration (Aksenov, 1972). On the continental slope mapping, difficulties rise sharply, and there are not yet any good examples of detailed maps for large areas of the continental slope, although they will undoubtedly be compiled in the near future.

As mapping becomes more detailed, the necessary frequency of sample acquisition also rises, as does the level of processing detail, which requires application of more sophisticated methods and instruments for preliminary and laboratory sample study. It is important to note, however, that the proposed quantitative binary sediment classification and the method of cartographical representation are maintained in principle, for the whole range of map scales. Only the necessary details are added to granulometric and material composition maps, which makes it easy to compare maps of different scales.

Chapter 4. DISTRIBUTION AND COMPOSITION OF BOTTOM SEDIMENTS NEAR THE SHORES OF WEST AND CENTRAL AFRICA

The main data concerning sedimentation near the shores of West Africa, from the coast line to the pelagic zones of the Atlantic Ocean, are given below. The aim of this survey is to demonstrate, on specific examples from different regions, the principles of mapping of the sedimentation process, that were discussed in general in the previous chapter. It is necessary to show where and why it is possible and where and why it is impossible for sediments of one type or another to accumulate; how granulometric and material sediment content, their textures, the thickness of sedimentary bodies and other indicators of the sedimentation process, are interconnected and determined by environmental conditions; and vice versa, how sediments can be used to reconstruct environmental conditions of the past, i.e., for facies analyses.

Knowledge of the general mechanisms governing the sedimentation process permits not only correct mapping of sediments, and understanding of their interconnections, but also prediction of sediment distribution and content, which is particularly important. This is always necessary when mapping, as inevitably there are areas insufficiently covered by data, which require scientific extrapolation.

The climatic and tectonic peculiarities of West Africa, great variation in sedimentation depths, and various factors of the living and dead environment have lead to an accumulation of bottom sediments, that are quite varied in both material composition and coarseness. They are discussed below from the coarsest (coarse-clastic) to the finest (pelitic muds), with subdivisions within each granulometric type according to material content.

1. Coarse-clastic sediments (larger than 1 mm)

This type of sediment is very rare near the shores of West Africa, because of the zonation of sedimentary material preparation on the continent. Coarse fractions (gravel, pebbles, boulders) are formed mainly by mechanical rock disintegration, which is prevalent especially in glacial and moderate zones, where such material is delivered to the shore by ice or rivers. The main mode of transportation in arid zones is the wind, which cannot carry coarse-clastic material. In the equatorial humid zone chemical weathering processes are so rapid, that almost all coarse-clastic material, including river alluvium, is transferred into the pelitic fractions. Hence, under the particular conditions of West

Africa, situated in the tropical arid and equatorial zones of sediment formation, there is virtually no delivery of coarse-clastic material from land. Thus the main type of coarse-clastic material in the sediments of West Africa is biogenous material (shells, coral fragments, bryozoan).

Biogenous (shell and coral) sedimentary material is quite widely distributed on the African shelf. In particular, shells are often found on the shelf of Western Sahara (Spanish Sahara), which they cover densely from the shore to the edge. In terms of granulometric composition, shells correspond mainly to the gravel fraction (from 00.1 to 10 mm) and are characterized by high $CaCO_3$ content (from 60 to 90-95%) and slightly increased C_{org} content, with very low contents of Fe, Mn, silica and titanium.

In the equatorial humid zone (on the Guinea-Liberia shelf), coarse-clastic material occurs seldom and only extends over small areas. These are isolated spots of shells or coral fragments, or special coarse-clastic sediments (gravel-pebble with separate large fragments) at the bottom of underwater canyons and valleys. The age of this underwater talus is not clear, but an important role is played in its composition by products of laterite weathering, for which a very high content of Fe and Al is quite typical, due to the high content of gibbsite and iron hydroxides in the drainage system.

The gravelly sediments of canyons and underwater valleys near the shores of Guinea have been studied from 8° to 12° lat N. (Senin, 1970). Apart from gravelly material, they contain larger fragments of the laterite crust, with 30-60% iron hydroxides and a high Al content. They may be deposits left over from the period when the ocean level fell during the Quaternary glaciations (samples were taken at depths from 35 to 150 m).

2. Sands (0.1-1.0 mm)

Sands near the African shore extend from the coast line to about the 200 m. isobath, but they do not form a continuous border, being broken in many places by sections of fine-grained sediments. Muddy sediments are especially common near river mouths in the equatorial zone.

The width of the sandy belt is usually related to the shelf width: on narrow shelves sands occur only in the coastal zone, and vice versa, in places where the shelf widens, the sandy belt is also considerably wider. This happens in the regions near Conakry, and also near the Kunene River and further south up to the Agulhas Bank.

The distribution of sands along the shelf is related to a number of factors (delivery of sandy fraction material from the land, its dilution by other sediment components, dynamic interaction with the ocean, etc.). In recent years indisputable data have been collected to show that during the Quaternary and earlier, the ocean level fell more than once by 100-200 m., and that most of the sands and other corase-grained shelf deposits represent relics of the Quaternary. Sands appeared due to washing away of finer sediments under subaerial conditions, when layers of loose shelf deposits were raised above the ocean level.

It is less frequent for sands to be encountered at depths greater than 200 m., i.e., on the continental slope. In particular, they have been found at 300-500 m near the mouth of the Orange River, which is due to abundant delivery of sandy material from this river, and probably to the water level falling in the geological past.

Sands are also found locally on the tops of the underwater mountains and ridges, and in underwater valleys and canyons.

In terms of material composition, sands near the African shores typically fall into two groups: terrigenous (with a predominance of clastic material) and biogenic carbonaceous (mostly remains of carbonaceous organism, in particular mollusk shells, foraminifera, and some coral material). Transitional sandy groups are also encountered frequently.

Non-carbonaceous terrigenous sands have been found on the shelf of West Africa at depths down to 100 m., between Cap Timiris and Cape Verde. They are well-sorted, with mainly a quartz composition and small contents of $CaCO_3$, Fe and Mn. Their distribution is of course related to delivery of eolian sandy material from the adjacent land deserts.

Low-calcareous sands (10-30% $CaCO_3$) have been found at 150-200 m. near the shores of Morocco and near Dakar. Their calcareous part usually consists of crushed shelly material of mollusks, and the terrigenous part is clearly dominated by quartz and authigenous glauconite. The sands near Dakar contain many fragments of igneous rock; these calcareous and highly calcareous sands, in which the biogenous part dominates, are usually clastic shelly, in some places with a notable admixture of bryozoan fragments, planktonic foraminifera and coral-algal remains. Near the shores of Spanish Sahara (Seneraga), the $CaCO_3$ content is usually between 50 and 97%. Fine sands are the most common fraction; coarse and medium sands occur only over small sections.

In areas with well-preserved shells, the sands have a notable admixture of gravel-pebble fractions, and their granulometric composition even shifts towards coarse-clastic sediments. This is observed in particular on the shelf brow and the upper part of the slope, where whole shells predominate (depths from 110 to 200 m.). The prevalence of calcareous and highly calcareous sands, near fields of shell material on the shelf brow, is one of the characteristic features of West African sehlf sediments. Towards the shore they are usually replaced quite quickly by fine terrigenous sands. Fe, Mn and P depletion, as well as average C_{org} content, are characteristic for all varieties of shelly sands. They are usually coloured with dirty-grey and greenish tones. As the original material for their formation consists of shells, which are at stages of disintegration, the sorting of such sands is usually very low, for they always contain substantial shell fragments and even entire shells. It cannot be excluded, that these shelly sediments on the shelf brow of West Africa are the relics of the ocean level, falling during glaciation. As far as we know, the age of this shelly material has not yet been determined.

Sands in the southern arid zones of Central Africa differ somewhat from those described above. Because of the presence of a thick upwelling here (near the Kunene River and in Walfish Bay), we find glauconite sands, often enriched with P, Fe, amorphous silica and C_{org}, in addition to terrigenous and calcareous types of sands.

The upwelling zone is dominated by low-carbonaceous sands, among which spots of calcareous shelly sands are imbedded at 130-170 m. These sediments are coloured with greenish-grey and dark tones, and they are characterized by high contents of organic matter in the form of fish bones and teeth, flakes and mineral aggregates (glauconite and phosphates). The content of phosphate grains in a number of samples amounts to 70-75% by sediment volume, i.e., this is the sediment-forming component. Phosphorus contents are also very high in such cases - 20-25% P_2O_5 in a number of samples (Senin, 1970; Emelyanov and Senin, 1969; Emelyanov, 1973; etc). Simultaneously with the increase in the phosphate constituent, an increase in the content of other components is usually noted as well, in connection with the flourishing of diatom algae in upwelling zones: amorphous silica and organic matter.

Diatom development in upwelling areas suppresses foraminifera development in plankton (Lisitzin 1971, 1972, 1985; Lisitzin et al., 1967), and hence foraminiferal sediments, as well as shelly mollusks, are usually located beyond the boundaries of the main upwelling area, and define its periphery. Glauconite content in the sandy fraction reaches 70-90% in a number of samples, while in finer material (aleurites) it quickly falls to 20-30%, and then to individual grains.

The glauconite sands of Africa are usually black in colour, typically with high contents of P and Fe (up to 17%), as well as of organic matter and amorphous opal. Depending on the sorting of these sands, the admixture of opal material and C_{org} is sometimes higher and sometimes lower. The sandy fraction almost always contains a lot of fish bones, teeth and scales. As a function of P and Fe content, and also $CaCO_3$, here low-phosphatic and phosphatic, low-ferruginous and ferruginous sands, non-carbonaceous or low-calcareous, and rarely calcareous shelly sands are distinguished. The latter usually occur beyond the borders of the upwelling, at depths of 160 to 1600-1700 m. These sediments are probably related to the ocean level drops, and slipping of part of the phosphatic material and glauconite from the shelf down the slope. Beyond the borders of the upwelling zone, we find mostly high-carbonaceous and carbonaceous sands (at depths of 300-1700 m.), and foraminiferal sands with very low contents of glauconite and phosphatic grains, and also of organic matter and biogenic opal. These sands are very similar to those of underwater mountains and rises in deep-water basins. It is clear that, beyond the upwelling zone at slope depths of 300-500 m., the upwelling influence disappears and biogenic sediments here differ from those of corresponding climatic zones and depths of other regions of the Atlantic Ocean.

There are curious characteristic aspects of sand distribution in the equatorial zone. First of all, sandy areas are much smaller here than in any other climatic zone of the ocean, which is due to chemical weathering leading to more pelitic fraction. Secondly, sands here do not extend right from the shore in the form of continuous belts, but are usually separated from the coast line by strips of muddy sediments, forming spots or lenses in the middle or outer parts of the shelf. It is not infrequent for sandy areas to be covered by a thin layer from above (especially near river mouths).

The mineral content of equatorial zone sands is also unusual: we find here a sharp decrease in the clastic minerals complex, with preservation of only the most weathering resistant crust minerals. Thus, a large part of the sands here are pure quartz, often with a concentration of valuable placer minerals.

The fourth peculiarity is the specific hydrogoethite-chamosite-glauconite complex of authigenous minerals. Depending on the admixture of biogenous carbonaceous material, the sands range in composition from terrigenous (non-carbonaceous) to low -and high-calcareous. Fragments of laterite weathering crusts, the size of gravel and pebbles, are often found in these sands.

In the Gulf of Guinea non-carbonaceous sands in the coastal parts of the shelf are recent, while in the outer parts of the shelf they are relics. Apart from sands, buried soils about 12 thousand years old according to C_{14} dating, and ancient corals, aged 5.8-6.8 thousand years have been found here (Allen 1964, 1965; Allen and Welly, 1962). These soils were formed under subaerial conditions when the ocean level fell by more than 100 m. Coral development corresponds to the period of the last climatic optimum. The ancient coral banks were found at depths from 50 to 88 m. These and other data, collected by many authors, demonstrate that shelf sediments found themselves above the water level more than once in the Quaternary period, and that the factor of ocean level oscillations must always be taken into account when studying sediments on the shelf, the continental slope and the periphery of oceanic basins.

In the terrigenous part of sands, it is typical for quartz to dominate, whereas in moderate and especially in glacial zones, high contents of feld spar are typical. Strong chemical weathering in the equatorial zone leads not only to a predominance of pelites in terrigenous removal, but also to a rather characteristic heavy mineral composition, dominated by ilmenite, magnetite, zircon, rutile, brookite, anatase and tournaline, i.e. the minerals most resistant to weathering. Low contents of amphibole, pyroxene, garnet and epidote, which occur only in places of unweathered rock erosion, are typical. This latter paragenesis can serve as an indicator of the presence of unaerated or poorly-aerated rocks within the limits of the equatorial zone drainage system.

In the delta of the Niger River, and also in the coastal parts of the shelf of Cameroon and Gabon, very interesting authigenous formations, typical for the equatorial zone, have been found. Glauconite, chamosite, hydrogoethite, a large quantity of caprolite and other new formations have been described here (Porrenga, 1966, 1967; Caillere and Giresse, 1966; Giresse and Odin, 1973; Emelyanov and Senin, 1969; Emelyanov, 1970; Cloud, 1955; Burst, 1958 a, b; Hower, 1961; Giresse, 1965).

Similar ferruginous hydrogoethite-chamosite-glauconite sands have also been found near the mouth of the Congo River. They contain about 12% Fe and 0.15% P. Most of the iron is concentrated in brown hydrogeothite-chamosite concretions, from 2 mm to 0.05 mm in size, and in greenish-black grains of gauconite. The content of hydrogoethite-chamosite grains in the sandy fraction can be as much as 30-50%. There are also a lot of fish bones and large coprolites, which is evidence for high primary and secondary production in the equatorial zone. This also influences the chemical composition - the sands have high contents of C_{org} and phosphorus. Most of the hydrogoethite-chamosite-glauconite sands are fine sands, and quality as low-carbonaceous or non-carbonaceous by $CaCO_3$ content. Thus, they are low-calcareous-ferruginous-low-phosphatic sands. They have been studied at a number of stations at depths ranging from 50 to 162 m. (Types ..., 1975; Emelyanov and Lyakhin, 1973). It is known that placer deposits of diamonds and several other useful minerals are associated with sands along the African shores.

3. Coarse aleurites and fine aleuritic muds

Coarse aleurites usually separate the sandy strip from fine aleuritic muds and their distribution near the shores of Africa is limited. Like sands, they occur at two bathymetric levels, corresponding to the modern and glacial ocean levels: near the shore, and near the shelf brow, at depths from 150 to 500 m., and sometimes down to 1500 m. Coarse aleurites are most widely distributed in glacial and moderate humid zones. Near the African shore they are most common in the southern arid zone, and, in the form of narrow strips, in the northern arid zone. High-calcareous foraminiferal coarse aleurites, i.e., biogenous sediments, predominate here. In the equatorial zone they are replaced by terrigenous or low-carbonaceous varieties, and near river mouths they are enriched, as are sands, with the specific complex of authigenous minerals typical for the equatorial zone.

Authigenous minerals and material composition of coarse aleurites are quite specific in upwelling zones as well - here we find high contents of C_{org}, phosphorus and amorphous silica, due to substantial primary production. Hence in terms of material composition we can distinguish coarse aleurites that are low-ferruginous and ferruginous, low-siliceous and siliceous, while in terms of $CaCO_3$ content, as noted above, in addition to non-carbonaceous, we find low-calcareous (10-30%), calcareous (30-50%) and high-calcareous (more than 50% $CaCO_3$) coarse aleurites.

In the arid zones of the African shelf and slope on the whole, the same material grouping of coarse aleurites as for sands is typical. Alongside terrigenous and varieties of calcareous sediments, in the upwellings there are glauconite, low-phosphatic and also low-siliceous varieties. In the equatorial zone near river mouths, hydrogoethite-chamosite sediments are added to the terrigenous and calcareous. Low-siliceous coarse aleurites have been found in the upwelling zone of Walvis Bay, hydrogoethite-chamosite only in the equatorial zone, while glauconite sediments are widely distributed along the coast of South-West Africa.

The coarse aleuritic fraction usually has a very high sorting coefficient, as it is the one with the greatest mobility among all granulometric sedimentary fractions (Lisitzin, 1966). In the upwelling zone near the mouth of the Kunene River, at depths from 135 to 230 m., coarse aleurites, like sands, are characterized by high contents of elements related to phytoplanktonic abundance (P, C_{org}, Fe), and by a low Mn content. In the mineral composition the role of indicators is played by glauconite and phosphates, and in the biogenous part by diatom algae shells, organic accumulations, and very often low $CaCO_3$ contents (up to 30%).

Fine aleuritic muds, by their properties and distribution in the ocean, occupy the boundary between loose, incoherent deposits (sands and coarse aleurites) and muddy, coherent sediments. When wet they usually have a semi-fluid or viscous consistency, and are sometimes mouldable, like muddy sediments, while they dry into a compact mass, without separating into separate grains, as sands do.

Fine aleuritic muds are distributed considerably more widely near the African shores than coarse aleurites, and they usually replace the latter both along the coast (as depths increase), and in the upper part of the continental slope. On the ocean side they are usually contiguous with aleuritic-clayey and clayey muds.

In the equatorial zone aleurites are found at small depths near river mouths, which reflects the delivery of large amounts of finely-dispersed products of weathering to river mouths of the equatorial belt. Fine aleuritic muds are spatially related to coarse aleurites, and their material-genetic types are also similar.

Like coarse aleurites, they are most widely distributed in arid zones, especially in the south arid, and much less so in the equatorial humid. Non-carbonaceous and low-carbonaceous varieties are the most common, and in upwelling areas - low-siliceous and siliceous, enriched with carbon (usually greenish-grey and dark green). Here we also find low-phosphatic (0.5-5% P_2O_5), as well as low-ferruginous varieties. It is typical for fine aleurites of upwellings to be greatly enriched with diatomic algae shells: the largest shells become part of the coarse-aleuritic fraction, smaller ones of the fine-aleuritic, and fine fragments of spines and shells - of the pelitic. As the content of pelitic fraction in the sediment increases, so does the content of

C_{org}, for a correlation exists between C_{org} and pelitic fraction contents. In fine aleuritic muds the pelitic fraction content is usually in the 30-50% range, which results in low sorting coefficients.

In the equatorial zone, as noted above, non-carbonaceous and low-carbonaceous fine-aleuritic muds are distributed (at depths of 30-70 m) with the special complex of authigenous minerals (hydrogoethite-chamosite-glauconite). For terrigenous clastic minerals, a complex of the most weathering resistant minerals of the light and heavy fraction is typical, and also an equatorial complex of clayey minerals (usually with high contents of kaolinite and gibbsite). Authigenous minerals are found in the form of pseudo-oolites, formed on the basis of caprolites.

4. Aleuritic-pelitic and pelitic muds

These are the two most finely-grained granulometric sedimentary groups in the binary classification: they respectively contain 50-70% and more than 70% of the fraction finer than 0.01 mm. Aleuritic particles account for 10-30%, and sandy for 1-20% of their composition. Aleuritic-pelitic muds are the more common, being most frequently situated on the lower part of the slope extending from African shores, and then replaced by pelitic muds in abyssal basins. In the equatorial zone, where pelitic material is delivered from land by rivers, muds come very close to the shores, especially near estuaries and deltas. In arid zones the most common varieties by material composition of aleuritic-pelitic muds are the calcareous and high-calcareous, consisting mainly of shells of planktonic foraminifera and their fragments. Within the boundaries of the Moroccan shelf and the continental slope of Mauritania, there are also low-calcareous varieties of these muds, with glauconite, organic matter, P and Fe, i.e., elements clearly indicating the presence of an upwelling (Senin, 1970). The same features are displayed by aleuritic-pelitic muds of the southern arid zone of Africa near Walvis Bay and the Kunene River. Authigenous minerals in the fine fractions here echo the peculiarities of the mineral composition of sandy and aleuritic sediments, as described above, while the chemical composition also reflects the specific properties of upwelling deposits.

In the terrigenous part of arid zone muds, eolian material plays a significant role, and not so much the coarse fractions (more typical for local and regional fallout, and usually represented by grains of sandy-aleuritic granulometry), but finely-dispersed, pelitic ones. Aerosol of pelitic size is evacuated from the Sahara and Kalahari and is transferred further to the west across the whole Atlantic Ocean, crossing South America and even reaching the arid zones of the Pacific Ocean (Lisitzin, 1978). This is confirmed by comparisons of the mineral and chemical compositions of aerosols, water suspensions and bottom sediments (Delany et al., 1967; Chester et al., 1972; Serova et al., 1979; Lisitzin, 1978). As characteristic indicators of areas of aerosol origination there are also mineral-indicators, and especially spores, pollen and remains of aerial plants from African deserts and steppes. That is the basic distinction between sediment formation in arid zones and the adjacent moderate humid and equatorial humid zones: most of the terrigenous material is delivered to the ocean by the eolian path, and not by rivers, which are virtually absent in arid zones (with the exception of intermittent rivers). The way terrigenous material is prepared and transported in arid zones is also reflected in the outlines of terrigenous mineral provinces in sediments - they lose their dependence on river mouths, and become wider and more uniform, reflecting the specific nature of aerosol transport. Aerosols do not reach humid zones in large amounts, as they are quickly washed out from the atmosphere by rain.

In upwelling aleuritic-pelitic muds (Walvis Bay), distributed over the shelf at depths of 70-100 m., amorphous silica content reaches 30-40% and more, i.e., these are low-diatom and diatom oozes, alternating in the form of spots with even finer pelitic diatom oozes. These are greenish-grey and green sediments of semifluid consistency with an acrid hydrosulphuric odour. Their sandy-aleuritic fractions contain wholeshells of diatom algae, phosphatic and glauconite grains, and fish bones, teeth and scales. It is in these oozes that the highest C_{org} contents for the whole Atlantic Ocean have been found - up to 10-12% and sometimes a bit higher (Types ..., 1975); Baturin, 1969, 1978; Baturin et al., 1970; Emelyanov and Baturin, 1975; Senin, 1970). These oozes have a low carbonate content. Upwelling oozes are distinguished from diatom oozes of the Antarctic by their complex of diatom algae, a very high content of P, the restoration environment, and in particular, high contents of C_{org} and fish remains.

In the equatorial zone near river mouths, as for sandy and aleuritic sediments, it is typical to find aleuritic-pelitic muds with the hydrogoethite-chamosite-glauconite mineral complex, and a terrigenous complex of the most weathering resistant minerals in the heavy and light subfractions. Apart from mineral composition, they also have a characteristic chemical composition: high contents of P (up to 0.2%), Fe (up to 11%), C_{org} (up to 3.5%), and in contrast with arid zones - low contents of amorphous opal. Depending on the Fe content, low-ferruginous and possible ferruginous varieties of these muds are distinguished. By $CaCO_3$ content, these muds are usually non-carbonaceous or low-carbonaceous (as distinct from arid zones, where the low-carbonaceous and carbonaceous are more common). Apart from the shelf, as noted above, this type of mud is widely distributed over the African continental slope, where it reaches depths of 1-4 thousand metres. In contrast with the shelf, calcareous and high-calcareous foraminiferal muds are the most common on the slope. By mineral composition (clastic and clayey minerals) they correspond on the whole to shelf muds, but with a considerably smaller mineral content.

Pelitic muds are the finest granulometric sediment variety, with a finer than 0.01 m. fraction content of more than 70%, and sometimes more than 90%. By distribution in the Atlantic Ocean they are second to aleuritic-pelitic muds, and occur in greatest amounts near the base of the continental slope and in deep-water basins, right down to maximal depths.

Clayey muds are found on the shelf only in the equatorial zone, especially in rivers near their mouths, and also in bays and lagoons. They are virtually absent from the shelf of arid African zones, with the exception of individual spots and strips in upwelling zones (especially in Walvis Bay). Carbonaceous and high-carbonaceous varieties composed of foraminifera and coccolithoforids, are the most common. Living foraminiferal shells are concentrated in the sandy-aleuritic fractions, but after their death they quickly disintegrate into small fragments and separate constituent crystallites, which can be seen when sediments are studied with a scanning microscope. Their second main constituent are coccoliths, with sizes corresponding to the pelitic fraction. There is a certain amount of zonation in the distribution of foraminiferal and coccolithic mud constituents: coccoliths are more common in arid zones and foraminifera in the equatorial zone. Moreover, diatomic algae of the equatorial complex and radiolarians are typical as admixtures in pelitic muds of the equatorial zone; they never occur in arid zones (except in upwellings).

For the material composition of pelitic muds (and partly aleuritic-pelitic), vertical zonation is very typical, related to the critical depth of carbonate accumulation, below which carbonaceous material does not penetrate due to rapid dissolving. The composition of the non-carbonaceous part of foraminiferal and foraminiferal-coccolithic muds, lying above the critical depth, is virtually indistinguishable from red abyssal clays in the same region. Abyssal clays represent so to speak the decarbonised part of these sediments, as can be easily tested at particular stations, by dissolving the carbonaceous part of pelitic muds with muriatic acid, and thereby obtaining "synthetic red abyssal clay".

In pelitic muds of arid zones the eolian material constituent is quite significant: in some cases it is predominant and in others it is of primary importance. Thus the non-carbonaceous part of arid zone pelitic muds is eolian.

The composition of the non-carbonaceous part of pelitic muds in the equatorial humid zone is significantly different. Here the fine material of equatorial zone weathering crusts is concentrated, as can be seen from the mineral and chemical composition. Red abyssal clays thus accumulate the finest material of the corresponding zones, including not only fine volcanogenic material, but also frequent admixtures of cosmogenic material, which allows us to classify them in the genetic type of polygenic sediments. The great depths at which red clays occur determines their extremely low C_{org} content (usually less than 0.25%). Organic matter produced by plankton is almost completely disintegrated in the water while falling to greater depths, and therefore an oxidizing environment is always typical for abyssal clays, which determines their reddish or brown colouring and certain other properties as well.

Chapter 5. MODERN AND ANCIENT INTERPLAY BETWEEN THE ENVIRONMENT AND SEDIMENTS

Recent sediment-environment interplay. Facies analysis

Sediments are related to environmental conditions by thousands of invisible threads, with zones representing the most general sets of conditions. Changes in conditions in the latitudinal plane are reflected in rough terms by changes in latitudinal (climatic) zones, changes in conditions along the vertical line are expressed through vertical zonation, while changes with increasing distance from continents are determined by circum-continental and tectonic zonation.

Since sedimentation conditions are simultaneously facies conditions, the study of modern and the reconstruction of past facies conditions amounts to facies analysis, and (climatic, vertical, circum-continental) zonation amounts to facies zonation, as if there were a coordinate system in the ocean, defining precisely the location of each facies, and helping to determine it in a three-dimensional system. The study of zonation will undoubtedly develop further, as new methods are elaborated, as understanding of sedimentary formations deepens, as new criteria appear for finer zone subdivision and as scientists acquire new ways of reading the record of the past, preserved in sediments. Competent sediment mapping, with regard for environmental conditions, i.e., all types of zonation, corresponds to the basic principles of facies analysis.

Ancient sediment-environment interplay. Paleooceanology

Sedimentary material preserves a record of environmental conditions, defined mainly by latitudinal position and depth; it is as if it remembers them, so that the study of ancient ocean conditions from sediments has developed on a wide scale. This new trend in the Earth sciences, has been named paleooceanology. At present it is developing rapidly and will no doubt become the basis for a new historical geology. The establishment of close correlations between climatic, abyssal (vertical), circum-continental and tectonic sedimentary properties, and specific latitudinal zones in the ocean has made such progress, that they are used to establish plate movements in the past, with transitions through various climatic zones, reconstruction of the paleodepth, tectonic conditions, etc.

The basic material for such constructions provided by long cores obtained by coring tubes, and especially cores from deep-water drilling. In recent years the study of drilling cores has been increasingly supplemented by the study of natural underwater exposures with the help of manned underwater vehicles.

When working near the shores of West Africa, one should take into account the enormous available core material, acquired during oil drilling, because it has been used very little for mapping.

A comparative-historical approach to mapping allows for deeper understanding of the mechanisms of modern sedimentation, and explains the origins of relic and mixed sediments.

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